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NAVSWC TR 90-532

UNDERWATER BLAST EFFECTS FROM EXPLOSIVE SEVERANCE OF OFFSHORE PLATFORM LEGS AND WELL CONDUCTORS

BY JOSEPH G. CONNOR, JR.

RESEARCH AND TECHNOLOGY DEPARTMENT

15 DECEMBER 1990

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NAVAL SURFACE WARFARE CENTER

Dahlgren, Virginia 22448-5000 • Silver Spring, Maryland 20903-5000

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EXECUTIVE SUMMARY

This report summarizes observations of the underwater shocks produced during the explosive removal of a hydrocarbon production platform from the Gulf of Mexico. Shock pressure measurements were made by Naval Surface Warfare Center (NAVSWC) personnel in December 1988. The entire operation was monitored by National Marine Fisheries Service and Minerals Management Service personnel.

The West Delta 30 platform was located 10 miles offshore south of Grand Isle, Louisiana, and was installed by the EXXON Corporation in 1964.

Shock measurements on 27 of 35 detonations were made at three depths and four ranges from the platform. A gauge line 290 feet long was attached to the platform for each series of severance explosions. The range from each explosion to the first gauge station varied widely because other structural members were in place between the explosion and the gauge string.

Charges weighing 25, 38, and 50 pounds were used. The choice was made on the basis of pile construction: the minimum charge necessary to sever the pile was used in each case. No significant difference was noted in the parameters of the shock waves propagated into the surrounding water.

Two types of tubular members were explosively severed below the mud line:

- Jacket leg piles and skirt piles: each consisting of a single layer of steel.
- Well Conductors: each consisting of several concentric steel layers with grouting between layers.

Each of these two general types can be further divided according to the location of the upper (open) end: some were in air and some were underwater.

All the below-bottom severance detonations produced a direct shock wave pulse and a pulse from the explosion product bubble collapse. The peak overpressure of the direct shock pulse was two to ten times greater than that of the bubble pulse. However, because of the longer duration of the bubble pulse, impulse and energy delivered by both the direct shock and the bubble pulse were comparable to one another. At 400 feet from the platform, the shock parameters were less than 10 percent of the values expected at the same range from a free water Pentolite detonation of the same weight.

In addition, precursor pulses, cavitation closure pulses, and smaller pressure excursions of indeterminate origin were observed. All these were of lesser amplitude than the direct shock and bubble collapse pulses.

When present, the precursor pulses appeared just before the direct shock pulses. Precursors seem to be a feature of the severance explosions in underwater stubs: those members whose open tops were underwater when the severing charge was fired.

Severance charges were fired at depths below the mud line of 8, 16, and 26 feet. No significant difference was noted in the parameters of the pressure pulses generated by these charges.

FOREWORD

The underwater explosion measurements discussed in this report were conducted by the Explosion Dynamics Branch (R15) of the Energetic Materials Division (R10). The work was supported by the Minerals Management Service, U. S. Department of the Interior.

Facilities were provided by Offshore Petroleum Industries (OPI) under contract to EXXON Corporation, with whom the responsibility for platform removal lay. Explosive charges were supplied, armed, and fired by DEMEX International under subcontract to OPI.

Underwater explosion data were collected and analyzed to determine the underwater shock output levels near under-bottom well and piling severance explosions. All shots were fired in the Gulf of Mexico at the former location of EXXON's West Delta 30 platform. Data were recorded and analyzed with the R15 digital data acquisition system.

Company and trade names are mentioned in this report for information and identification purposes only. Endorsement or criticism is not intended.

The R15 field crew included: R. E. Mersiowsky, D. R. Kulp, S. E. Coghill, K. W. Rye, and J. G. Connor, Jr. Gauges were constructed, calibrated, and repaired as needed by S. E. Coghill at the Naval Surface Warfare Center (NAVSWC), Dahlgren. Preliminary setup and rig construction were also done at Dahlgren by R. E. Mersiowsky, B. A. Robey, and B. E. Sebring.

Digitization of analog tape records and final computer analyses were run at the NAVSWC, White Oak site, by R. B. Tussing, T. K. Fackler, J. L. Johnson, D. L. Kulp, and J. C. Floyd.

Approved by:

W. H. Bohli

W. H. BOHLI, Head
Energetic Materials Division

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CHAPTER 1

INTRODUCTION

BACKGROUND

The Code of Federal Regulations requires that oil and gas production platforms no longer in use be removed within one year of abandonment. Those platforms that have depleted hydrocarbon reserves on the lease are subject to this regulation. All structural elements must be cleared to at least 15 feet below the mud line to avoid leaving navigation obstacles and snags for fishermen's nets.

Platform removal is most efficiently and cost effectively accomplished by detonating an explosive charge inside each of the various hollow supporting members that penetrate the sea bottom. Following severance of the structure, submerged portions are pulled from the water and placed on barges for removal and disposal. It is required that the explosive severance operation be carried out with minimum effect on marine life.

Two aspects of the explosive structure removal operations remain largely unquantified: the threshold shock pressure, impulse, or energy levels at which marine life is damaged, and the actual levels found near typical severance activities.

The present project was designed to examine the second of these: determination of the shock wave levels output during a typical explosive removal operation. In this report, discussion is limited to evaluation of shock output levels at various positions; consideration of the consequences to marine life forms is left for others. The original plan was to conduct controlled half-scale tests in the Potomac River at Dahlgren, Virginia. The properties and construction of the hollow members driven into the mud bottom would have been well known and documented, and the locations of the gauges used to examine the shock fronts would have been known to within a few inches. There was also a plan to tether biological specimens near explosion sites at known standoffs; the specimens were to be examined after each shot to determine the extent of their injuries, if any. Ecological considerations precluded execution of this plan as well as testing anywhere in the Chesapeake Bay or its tributaries–including the Potomac River.

A production platform scheduled for removal was found which could be instrumented without undue interference with removal operations. All parties involved were willing to allow diagnostic shock pressure measurements.

WEST DELTA 30 PLATFORM

The West Delta 30 platform was installed in 1964. Its reservoirs had been depleted by the mid-eighties, and it was scheduled for removal by a subcontractor to the EXXON Corporation in the fall of 1988. It was located about 10 miles offshore in the Gulf of Mexico south of Grand Isle, Louisiana.

Dimensions of the platform are shown in Figure 1-1. It was located in 53 feet of water. The bottom penetrations included the main piles for two 6-leg platform jackets, eight skirt piles (used for initial positioning of the jacket), six dolphin piles (used as bumpers for supply vessels during platform operation), and nine well conductors (through which the hydrocarbons were pumped out). As many as 14 conductors were used during the active lifetime of the platform; only 9 remained at the time of the removal operation.

DERRICK BARGE OPERATIONS

Vessels were supplied by Offshore Petroleum Industries (OPI) for the removal of the West Delta 30 platform. The flotilla consisted of several tug boats, a supply boat, and a barge. The barge, "DB II," was the primary staging platform for welders, divers, and riggers who removed the platform. It is a derrick barge approximately 350-foot long by 125-foot beam. The barge was held on location by six anchors on 1000+ foot cables. Position was adjusted by operating a steam winch on each anchor cable. The DB II carries a crane capable of lifting the severed six-leg jacket from the water after the divers, riggers, and ordnance crews completed their tasks. It also provides sleeping and eating facilities for off-duty personnel; each of two crews worked a daily 12-hour shift so that operations continued 24 hours a day.

The first step in the operation was the removal of the superstructure– everything above the jacket legs. Completion of this effort left the jacket legs extending about 10 feet above the water. Two well conductor tops were at 45 feet below the water surface; the tops of the other conductors were approximately 20 feet above the water surface.

Next, mud and silt were "jetted" from the inside of each bottom penetrating piling to be removed on a given shot. Each charge was armed and lowered to a prescribed depth in the structural member being severed.

For each detonation sequence, when the charge(s) had been placed and armed, the anchor winches were used to pull the barge away from the platform as the Naval Surface Warfare Center (NAVSWC) crew paid out the gauge string and cables. Barge motion was controlled closely enough that the long axis of the vessel remained parallel to its original position beside the platform. That is, the steam winches were capable of maintaining the barge axis parallel to its original direction as it was moved away from the platform.

The placement of the instrumentation van used by NAVSWC for the underwater pressure measurements is shown in Figure 1-2. The barge is shown in the figure standing off from the platform in position for firing. Upon completion of firing, the anchor winches were used to move the barge back next to the platform. There, the riggers, divers, and ordnance personnel prepared for the next shot by removing the severed portions of the structure, jetting mud from the next piles to be severed, and setting new charges.

CHARGES

All the charges were Composition B and were prepared, armed, and fired by DEMEX International--a subcontractor engaged by OPI.

The well conductors were severed with 25-pound cylindrical charges. One, however, was cut with a 50-pound toroidal charge. The jacket leg main piles and skirt piles were all cut with 38-pound octagonal charges whose construction is indicated in Figure 1-3.

Charge Confinement

Platform design drawings were not available, so the structural details of each of the bottom penetrating members are not known. Only limited seawater corrosion is expected because cathodic protection is required on such structures. The bottom penetrating members were roughly equivalent to one another in their shock attenuating capabilities--with the exception of the well conductors which included cement grouting between layers of steel pipe.

Skirt Piles. These consisted of 30-inch diameter steel pipes with 1-inch wall thickness. Their tops were 33 feet above the sea bottom (20 feet below the water surface).

Jacket Piles. These were part of a structure fabricated on shore, carried by barge to the site, and set in place to provide a work platform for the hydrocarbon extraction operations. Each jacket was held in position by a main pile driven through each of its legs. There was, therefore, a single 1-inch thickness of 30-inch diameter pipe between the explosive and the surrounding mud since the jacket legs may penetrate the mud for only a short distance. At the time of removal, these legs (and piles) had been cut off about 10 feet above the water surface.

Well Conductors. These were 20-inch diameter pipes containing an 11-inch pipe with cement grout between the two layers. Two of the six were "underwater stubs": their tops were 45 feet below the water surface (8 feet above the sea bottom) rather than in the air above the water surface.

PRESSURE GAUGE STRING

Figure 1-4 shows the configuration of the gauge string. The outboard end is tied to a convenient point on the platform so that the submerged lines are not likely to become entangled in debris or portions of the platform below the water surface. This attachment method required that, for some shots, the close-in vertical gauge line be considerably more than the planned 10 horizontal feet from the location of the buried charge. In addition, due to subsurface currents, the gauge string could not be pulled straight without the possibility of overstraining, and possibly breaking, the cables.

Gauge Location

Locations of the gauges were estimated. The estimate begins with determining the horizontal standoff of the float above the first vertical down line from the nearest point on the platform. This gauge line (assumed vertical) was then located relative to the exact leg/conductor/pile being severed. Dimensions were taken from available drawings of the platform for use in these calculations.

An estimate of the curvature of the line of floats caused by water currents then provided estimates of the horizontal locations of each of the other vertical down lines. A 12-pound weight was attached to the lower end of each vertical line to counter its tendency to rise in the current. The vertical gauge lines were, therefore, assumed to be vertical.

There was no practical way to determine the actual standoff of the first gauge float from the platform. Because of the uncertainty in standoff distance and the unknown effects of subsurface currents, gauge locations are known only to within ± 5 feet.

Ranging Program. The NAVSWC ranging program is usually used to determine gauge ranges from a charge fired underwater. The program assumes a bare spherical charge fired in free water and uses an iteration technique to calculate the gauge ranges. A fiducial, or zero time, gauge must be mounted on the surface of the charge to signal the passage of the shock wave from the explosive into the water.

For the platform removal, all the charges were enclosed in steel tubulars of various thicknesses and were placed 8 to 26 feet beneath the bottom mud boundary. Thus the shock waves passed through steel, mud, and water between the detonating charge and the gauges. In addition, the fiducial gauges could not be mounted directly on the charges. As it developed, most of the fiducial gauges failed to produce usable signals because each was suspended a foot or so above the charge. Also, the gauge leads were probably severed by the shock from the primacord used to initiate the charges.

INSTRUMENTATION

Gauges

Natural tourmaline gauges are used for underwater shock pressure measurements because the material, unlike quartz, is not hydrostatically (bulk) sensitive; that is, it produces a response to changes in pressure, not to steady pressure. For this reason, precise gauge orientation is not critical to successful use.

Gauges fabricated at NAVSWC are used for in-house projects and sold worldwide.[1] Gauge configuration is shown in Figure 1-5. Each gauge consists of one or four thin cylindrical disks with a diameter between 1/8-inch and 2-inch, depending on the sensitivity required. (For the present tests, we used 7/8-inch and 1-inch gauge disks). The disks are cut, polished, and glued together in alternating layers with appropriate electrical connecting tabs. The tabs are soldered to leads projecting from a plastic "feed through." A Tygon sleeve filled with silicone oil is then sealed over the gauge elements and electrodes. The acoustic impedance of the oil/Tygon combination approximates that of water and has low enough electrical conductivity to prevent shorting the gauge leads.

Tourmaline gauges were mounted on 1/4-inch steel fingers about 12 inches long that were attached to vertical "down lines." Each down line was suspended from a float; each float was attached to the next by steel cable. On each line, single gauges were placed at 20, 35, and 49 feet below the water surface. Since the mud line was approximately 53 feet below the water surface, the lowest gauge on each string was about 4 feet off the bottom. The first down line was intended to be 10 feet (horizontally) from the charge location for each shot; in no case was it possible to place the line this close. The second line was 15 feet beyond the first; the third was 75 feet beyond the second; and the fourth was 200 feet beyond the third. The total horizontal arc length of the gauge line from the first to the fourth down line was therefore 290 feet.

Gauge signal cables were run to the surface along each down line and supported by surface floats enroute to the barge.

Electronics

The signals from the tourmaline pressure gauges were fed to impedance matching and termination networks via about 400 feet of special low noise coaxial cables. Signal conditioning circuitry placed the signals on a 14-channel RACAL analog FM tape recorder. The tapes were run at 120 inches per second, and the recorder frequency response was 500 kHz. Playback frequency responses of 500, 250, and 125 kHz were accessible by selection of playback electronics; 125 kHz was selected to minimize digitization memory requirements while maintaining accurate reproduction of shock wave rise times.

Immediately following each shot, the analog tape records were played back on oscilloscope chart recorders to assist identification of faulty gauges and to allow timely judgments of gauge condition and of the quality of the data as it was obtained.

SHOT LOG

Removal of the West Delta 30 platform required severance of the 35 bottom penetrators ("tubulars") listed in Table 1-1. Explosion shock waves were recorded for 26 of these events–all cut by charges inside the tubular penetrators. Those recorded and discussed in this report are assigned shot numbers which are shown in the left-hand column of the table.

The first six tubular members to be removed were the rust-weakened dolphin piles which did not extend as far into the bottom mud as the other tubulars. Following the dolphin piles, two well conductors (#2 and #6) were cut. These were considered familiarization shots for the NAVSWC crew and no shock wave recordings were made.

The last tubular removed (conductor #4) was cut with an externally mounted shaped charge–the only such charge used in this operation. The shock was not recorded because this would have provided only one sample with no replicates. The record of a single shot would generate more questions than answers.

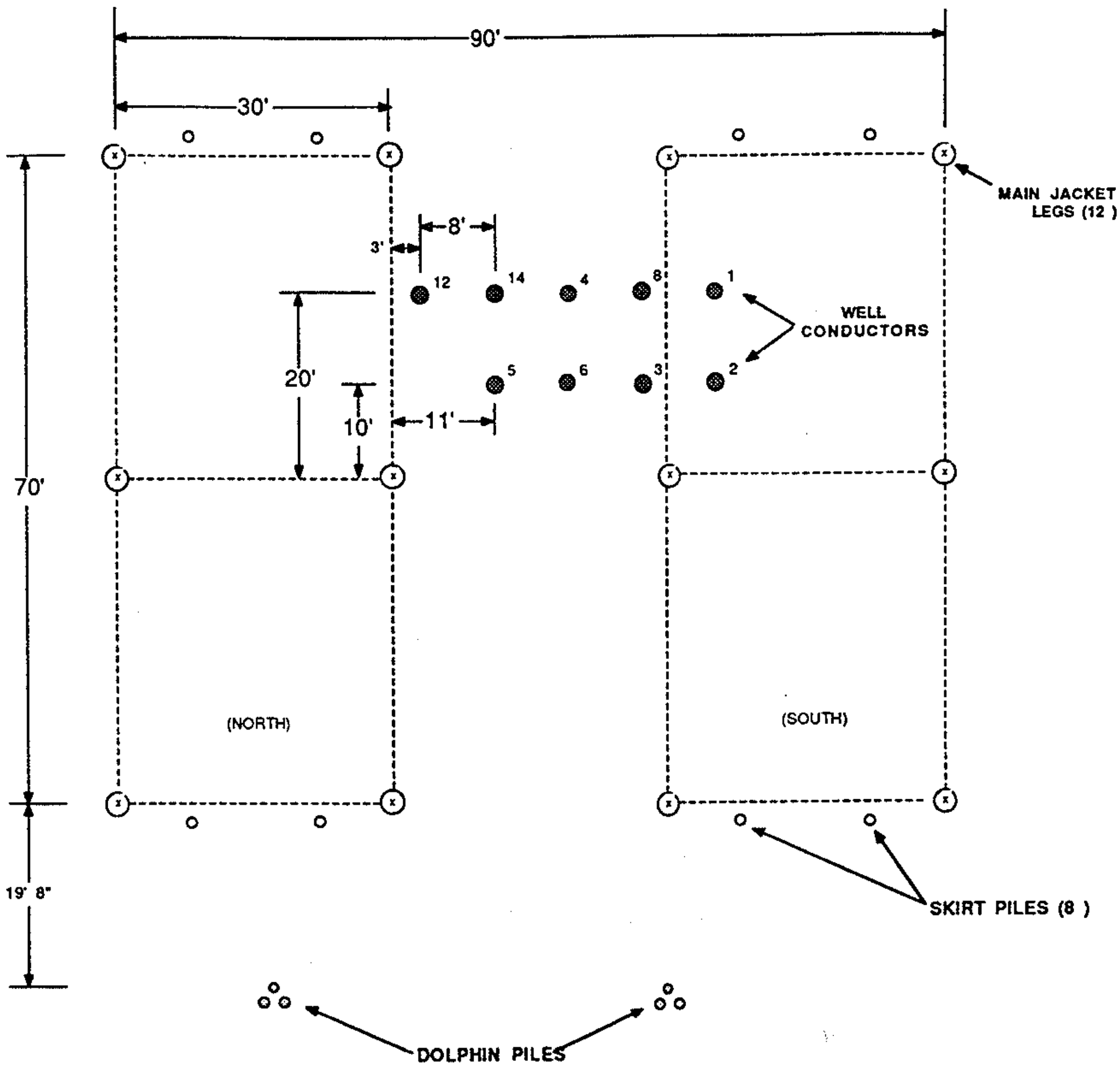


FIGURE 1-1. WEST DELTA 30 PLATFORM GEOMETRY

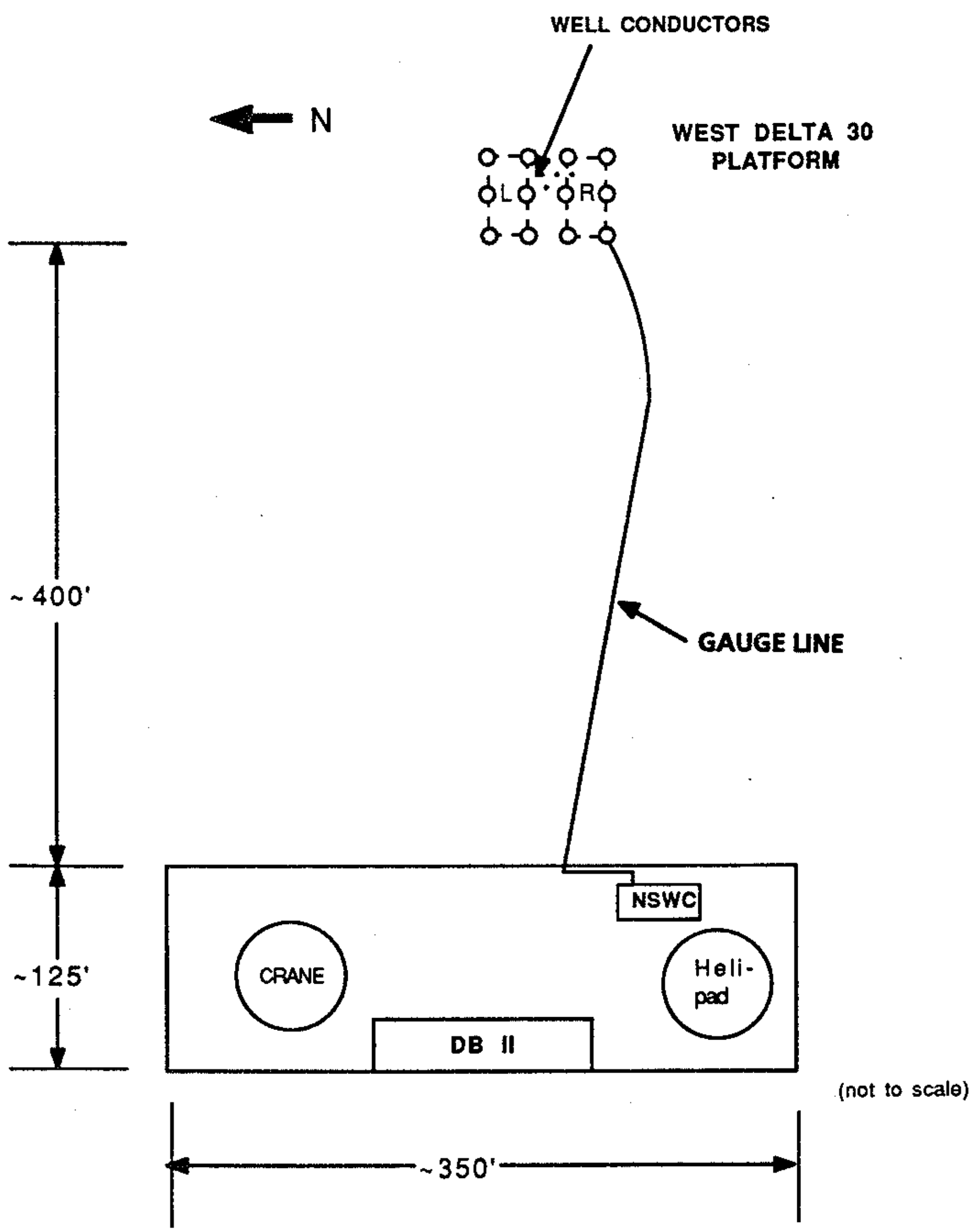


FIGURE 1-2. SCHEMATIC OF GAUGE LINE, BARGE, AND PLATFORM

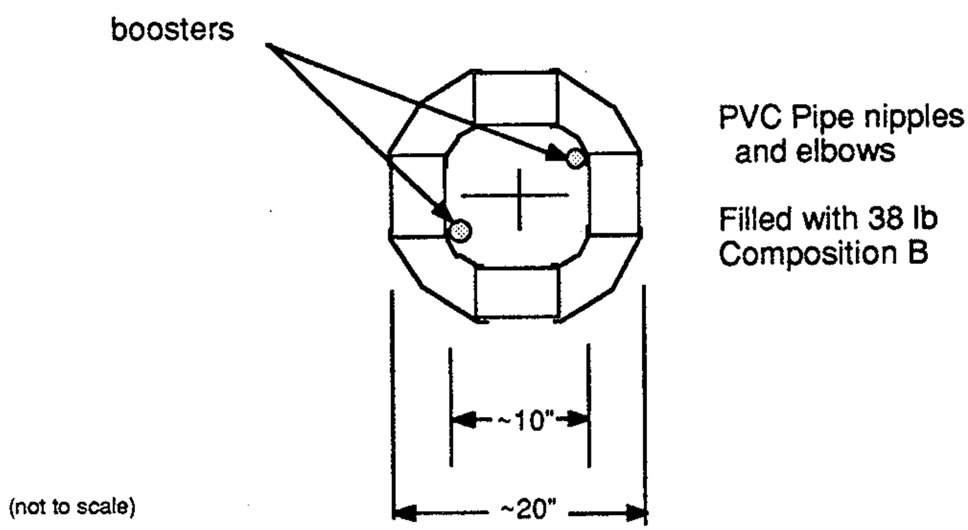


FIGURE 1-3. OCTAGONAL CHARGES

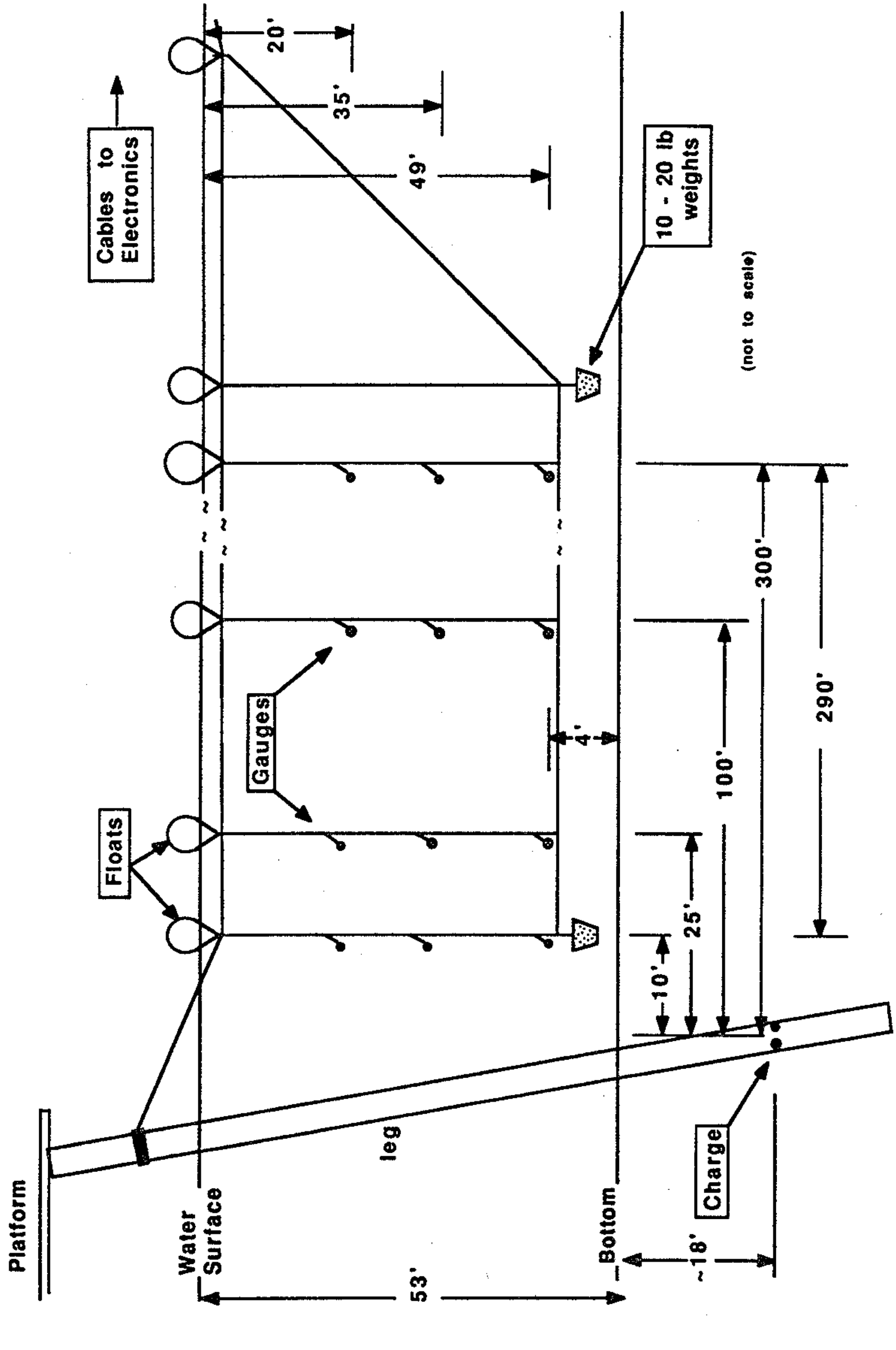


FIGURE 1-4. GAUGE RIGGING

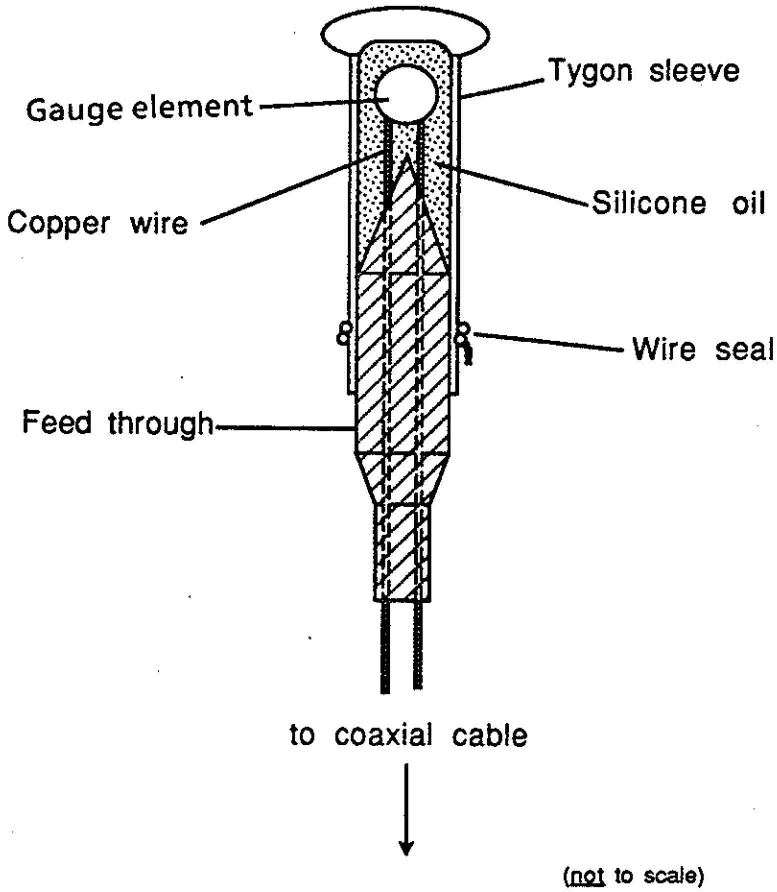


FIGURE 1-5. TOURMALINE GAUGE CONFIGURATION

TABLE 1-1 SHOT LOG

NAVSWC Shot No.	Date (1988)	Time	Charge Weight (lb)	Depth Below Mud (ft)	Top of Tube*	Target
--	12/11	1000-1300	40 ea	16	+5'	5 Dolphin Piles
--	12/12	0850	40	"	"	Dolphin Pile
		"	25 ea	"	+10'	Well Conductor # 2 & 6
2873	12/12	1131	25	18	-45'	Well Conductor # 8
2874	"	1239	25	18	-45'	Well Conductor #14
2875-1	12/13	0900	50	20	> +10'	Well Conductor # 1
2875-2	"	"	25	20	"	Well Conductor #12
2876-1	"	1010	25	20	"	Well Conductor # 3
2876-2	"	"	25	20	"	Well Conductor # 5
2877	"	1123	50	20	"	Well Conductor # 1
2878-1	12/14	1403	38	16	+10'	North Main Pile
2878-2	"	"	"	"	"	"
2878-3	"	"	"	26	"	"
2878-4	"	"	"	16	"	"
2878-5	"	"	"	"	"	"
2878-6	"	"	"	8	"	"
2879	12/15	0725	38 ea	26	-20'	2 North Skirt Piles
2880	"	0727	"	16	+10'	6 South Main Piles
2881-1	"	0848	"	26	-20'	North Skirt Pile
2881-2	"	"	"	16	"	North Skirt Pile
2882	"	1015	"	"	"	2 South Skirt Piles
2883	"	1128	"	"	"	2 South Skirt Piles
--	12/16	0900	external shaped chg		+30'	Well Conductor # 4

* Approximate vertical separation from water surface:
> 0 : above water
< 0 : submerged, below water

CHAPTER 2

PREVIOUS WORK

Few quantitative studies of the explosion shock wave output from under-bottom detonations have been reported. Two which appear applicable to the present problem are discussed briefly in this section. Unfortunately, neither is readily accessible in the open literature.

The first study was a series of large free water Composition C-4 explosions. They were fired to accumulate shock data from which generalized similitude equations were generated.

The second study might be considered the genesis of the present project. Half-scale simulated well casings were severed with Composition C-4 charges under more controlled conditions than were possible on the West Delta 30 removal operation.

FREE WATER TESTS

Three 65-pound Composition C-4 charges were fired in free water in the Potomac River off Dahlgren, Virginia, as part of a broader series of tests. Results were reported in an internal memorandum and are summarized here.

Shot Geometry

Charges and gauges were placed on a float-supported string rig shown in Figure 2-1. Charges and gauges were all placed at a depth of 30 feet in 70 feet of water. Gauge ranges from each charge were 5, 8, 15, and 65 feet; these ranges correspond to reduced ranges of 1.24, 1.99, 3.73, and 16.17 ft/lb$^{1/3}$. Reduced range is defined as actual range in feet divided by the cube root of charge weight in pounds.

Results

Shock similitude equations were determined for these charges. The similitude equations express peak shock overpressure, specific shock impulse, and shock energy flux density as a function of reduced range.[2]

Peak overpressure is the maximum initial excursion from ambient of the pressure gauge signal when the shock wave arrives. Impulse is the integral under the pressure-time signal; the integral extends for five time constants of the initial decay. (The initial decay usually approximates an exponential.) Energy flux is proportional to the integral of the square of the pressure amplitude, again for a duration of one time constant.

The similitude equations determined for the 65-pound charges are:

Overpressure:

$$P = 27150\,(R/W^{1/3})^{-1.22}\ (\text{psi})$$

Specific Impulse:

$$I = 1.45\,W^{1/3}\,(R/W^{1/3})^{-.919}\ (\text{psi-sec})$$

Energy flux:

$$E = 2950\,W^{1/3}\,(R/W^{1/3})^{-2.13}\ (\text{in-lb/sq-in})$$

In these equations,

R = Range (ft) and W = Charge Weight (lb)

These results are presented graphically with the results of the well casing severance tests discussed in the next section.

HALF-SCALE WELL CASINGS

Several explosive tests using half-scale models of oil well casings were conducted by NAVSWC.[3,4] These tests were performed in the Potomac River at Dahlgren, Virginia, to determine the characteristics of the pressure field in the water near explosions confined in simulated well conductor casings. The casings were severed both in free water and with the charges 7.5 feet below the mud line.

Three explosives were used: Composition C-4, TNT, and Nitromethane. Of the three, Composition C-4 provided the greatest output levels. The results discussed here are from 7-pound Composition C-4 charges detonated 7.5 feet below the mud line.

Shot Geometry

Twenty-two tourmaline gauges were mounted on three vertical down lines spaced 4, 9, and 14 feet from the down line on which the charge and simulated well casing were mounted. A schematic diagram of the setup is shown in Figure 2-2. For the under-bottom shots, six of the gauges were on the bottom, three were just under the water/air boundary, five were near the bottom, and the remaining eight gauges were located at middle depths in 25 feet of water. The closest gauge was 10 feet from the charge; the farthest gauge was 28 feet from the charge.

The simulated casings were hollow, filled with water, and vented to the atmosphere above the water surface.

Results

Shock wave peak overpressure, specific shock impulse, and shock energy flux density were determined for each gauge. The results are presented in graphical form: overpressure in Figure 2-3, impulse in Figure 2-4, and energy in Figure 2-5. On the pressure-time signals from the half-scale tests, impulse and energy integrals were taken to 1 millisecond after shock arrival. Impulse and energy were calculated to five time constants of the initial exponential decay on the pressure-time signals from the 65-pound free water shots described above.

The upper line on each figure shows free field values determined from the 65-pound shots. The lower line represents a least square fit to the values obtained with the charge beneath the mud line in the half-scale, simulated well casings. No allowance was made for the mud fraction of the path between each charge and gauge. The only distinction made in the data presented is that the pressure values obtained from gauges within 30° of the vertical line above the charge cluster about a different, lower, line than those from gauges located farther from the vertical. Despite this, impulse and energy values from the gauges at angles greater or less than 30° are not clearly distinguishable from one another.

Pressure and impulse values for the mud shots, represented by the lower fitted values in each case, were reduced to about 36 percent of the values observed at the same reduced ranges in free water. Energy values were reduced to about 15 percent of the free water values. These percentages are a rough measure of the attenuation provided by the mud and pipe confinement. They are the ratios of the values of each parameter at approximately the mid-range of the measurements: 10 $ft/lb^{1/3}$.

The energy attenuation is considerably greater than that of either the impulse or the overpressure. This is reasonable because shock energy is proportional to the square of shock overpressure. When the pressure is reduced to 0.36 of its free water value, the energy should be reduced to $0.36^2 = 0.13$ of its free water value. The impulse (proportional to pressure) is reduced by the same amount as the pressure.

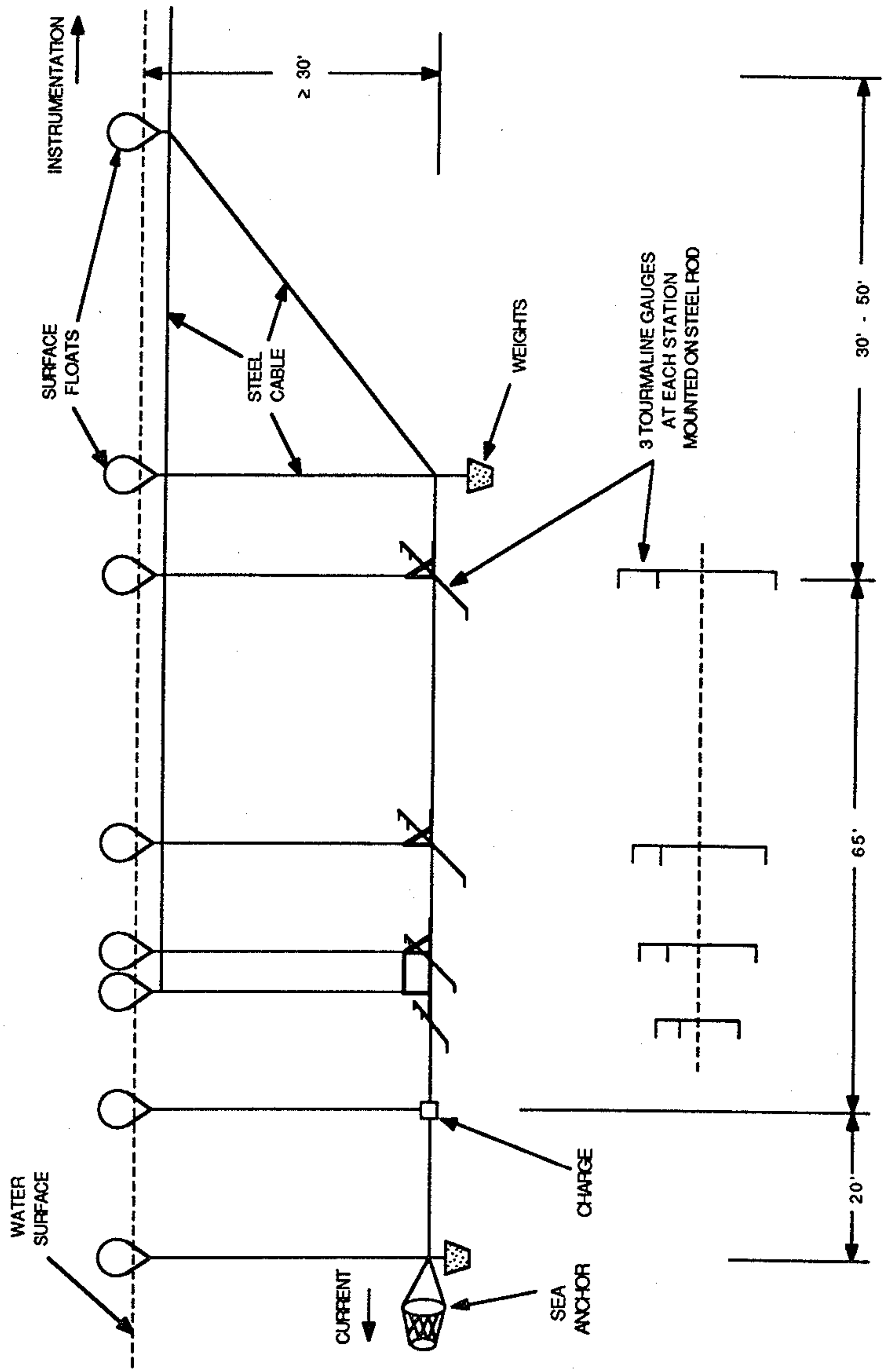


FIGURE 2-1. SIXTY-FIVE-POUND FREE WATER TESTING CONFIGURATION

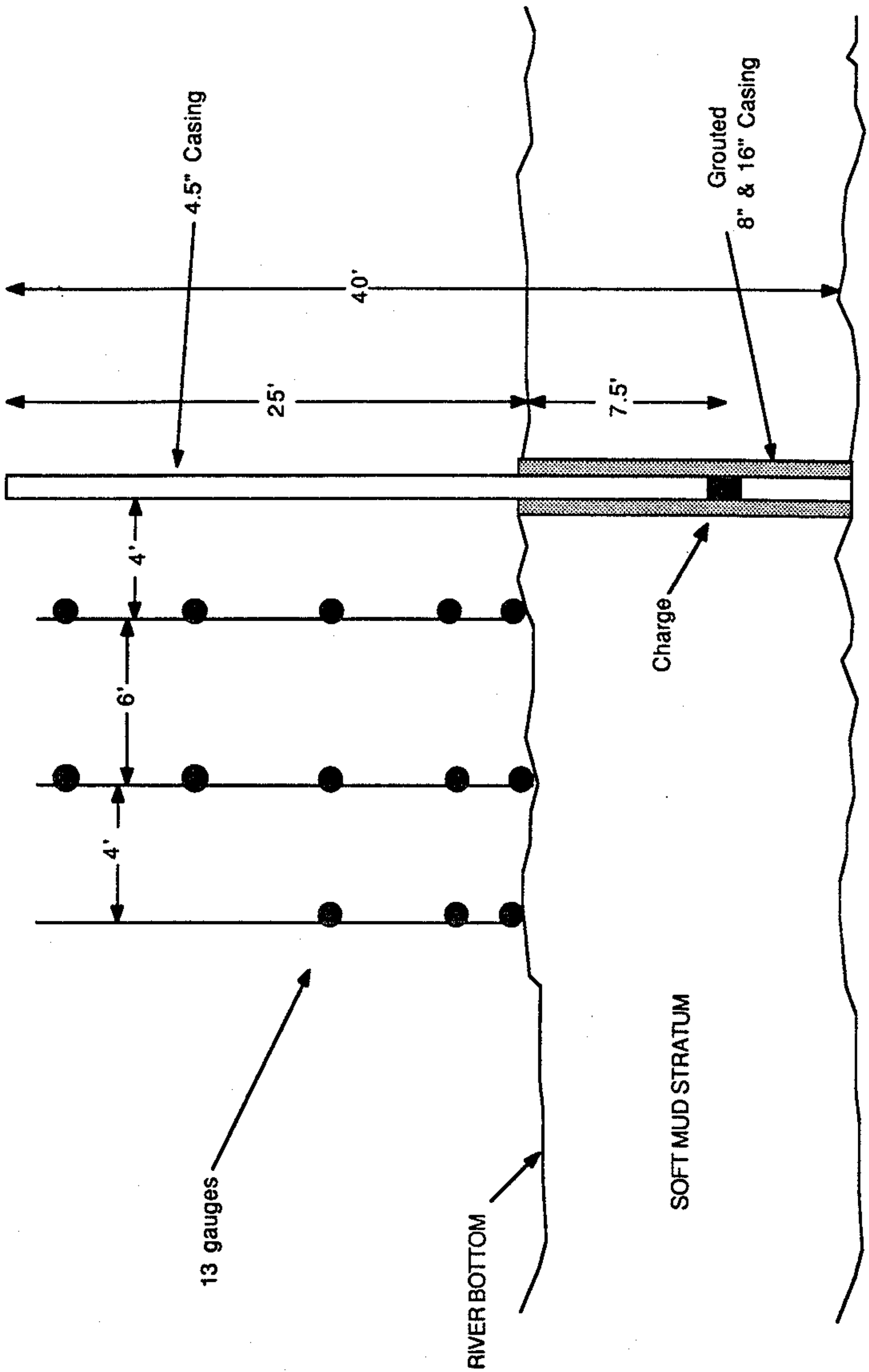


FIGURE 2-2. BURIED CHARGE TESTS

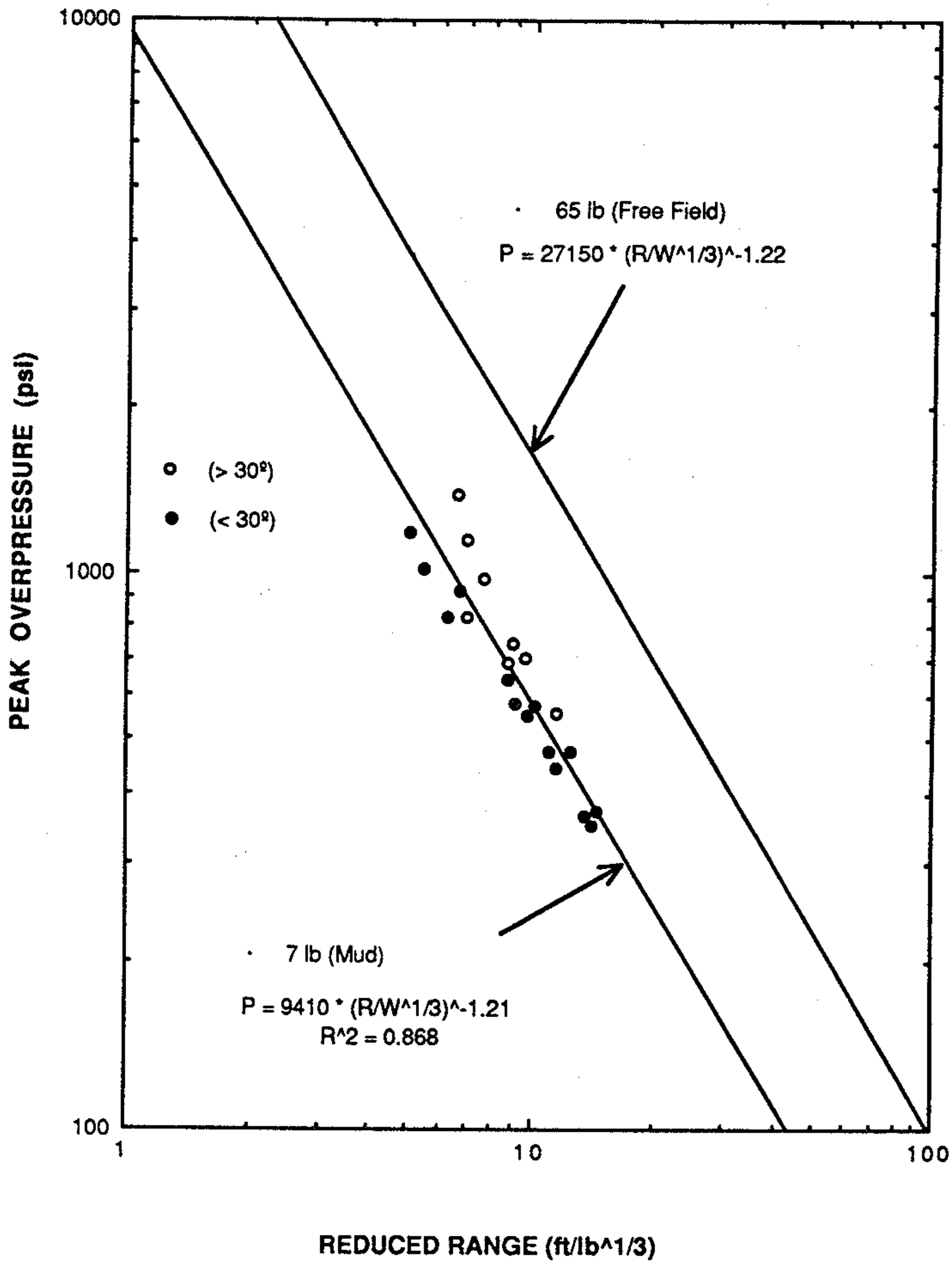


FIGURE 2-3. PEAK PRESSURE FROM HALF-SCALE BURIED CHARGE TESTS

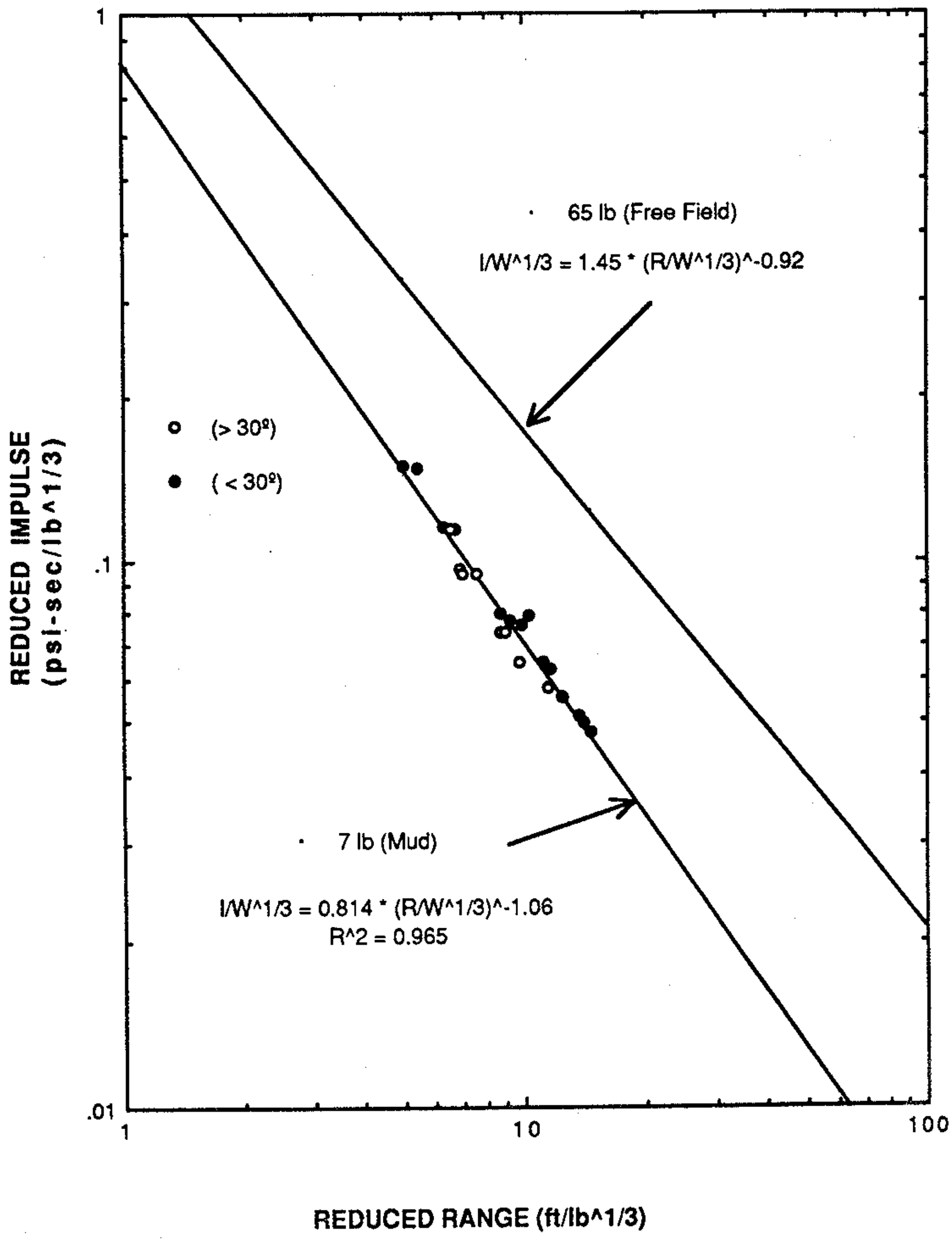


FIGURE 2-4. REDUCED IMPULSE FROM HALF-SCALE BURIED CHARGE TESTS

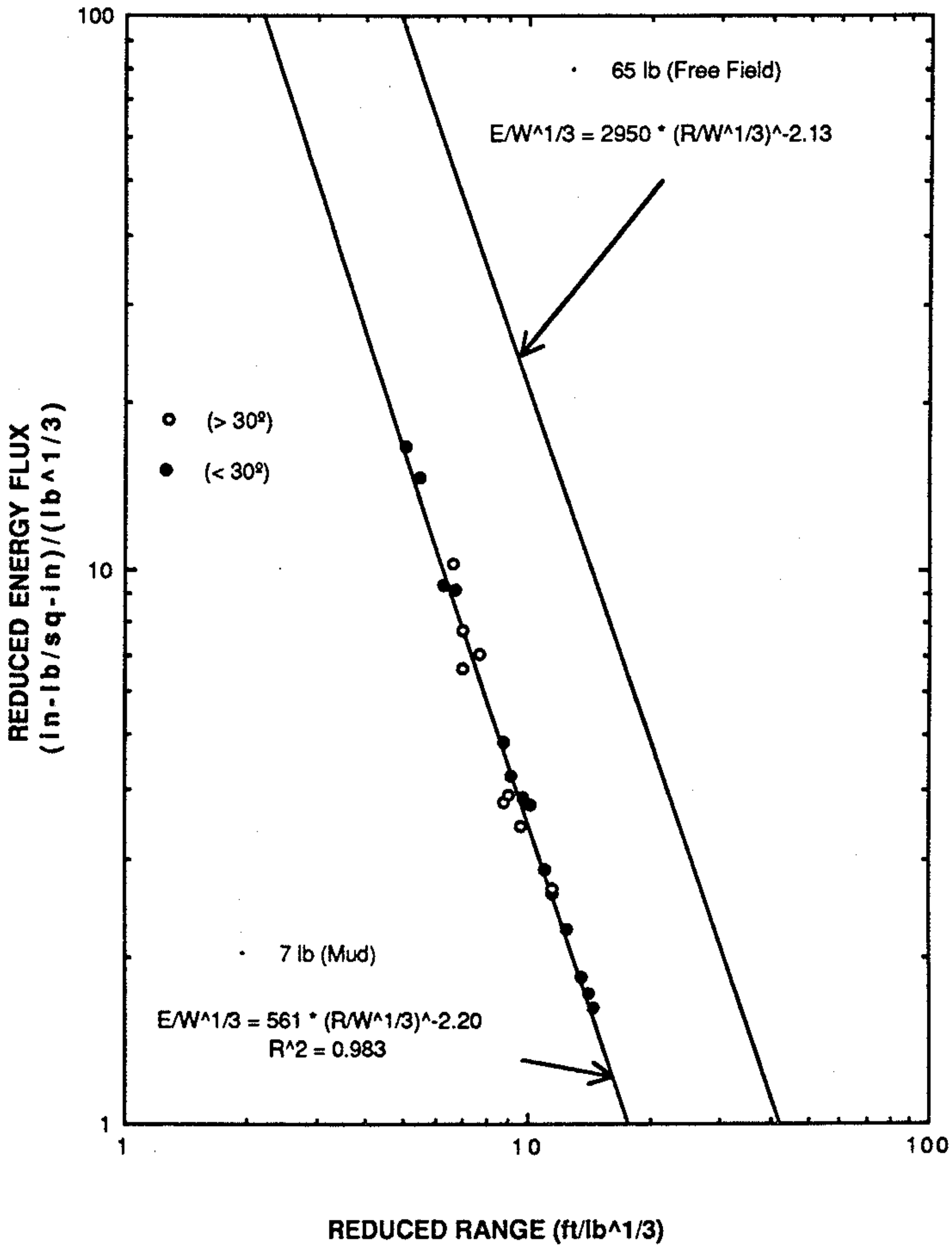


FIGURE 2-5. REDUCED ENERGY FROM HALF-SCALE BURIED CHARGE TESTS

CHAPTER 3

ANALYSIS PRELIMINARIES

This chapter presents several topics necessary for an informed consideration of the shock wave data presented in the following chapters. First, the geometric similarity principle and shock reflections and refractions are briefly discussed. Then a description of the gauge location algorithm is followed by a description of a "typical" underwater shock wave pressure-time record. Last, a basis for distinction among platform removal detonations is established.

UNDERWATER EXPLOSIONS

Two rather diverse background topics are outlined briefly in this section:

- Cube root, or geometric, scaling of the pressure fields around the usual underwater explosion test has been found to be a useful technique for combining the results of different tests.

- The number and amplitude of underwater shock pulses observed at gauges can be interpreted in terms of boundary reflections and shock refraction at velocity gradients in the water.

Similarity and Scaling

The principle of similarity allows comparison of shock wave pressure-time measurements from charges of different dimensions. Measurements of pressure are made at a distance, R, from a charge of particular dimensions at a time, t, after initiation; a new test is set up in which all the dimensions are changed by a factor L_0. The similarity principle states that pressure and other characteristics of the shock wave are unchanged if the length and time scales are changed by the same factor L_0.

For example, suppose the pressure and duration of the shock are measured 10 feet from a 1-foot diameter spherical charge. Similarity states that the same pressure will be measured 20 feet from a 2-foot diameter charge; the duration of the shock from the 2-foot charge will be twice as long as the duration of the shock from the 1-foot charge. Note that pressure does not change: the range and the time at which the pressure is observed both scale by the geometric factor.

Since the specific impulse and energy flux associated with the shock are proportional to time, they must also be scaled by the geometric factor.

Charge weight is proportional to volume, and the linear dimension of a charge is proportional to the cube root of its volume. Thus the linear dimension scale factor for a charge is proportional to the cube root of charge weight. For this reason, underwater explosion effects are usually reported in terms of "reduced" quantities: distance, time, impulse, and energy each divided by the cube root of charge weight. This technique effectively "reduces" all results to those to be associated with a 1-pound charge.

The similitude equations developed for a particular explosive are of the following form:[1]

Peak Overpressure: $P = K_p\,(R / W^{1/3})^{A_p}$

Specific Impulse: $I / W^{1/3} = K_i\,(R / W^{1/3})^{A_i}$

Energy Flux: $E / W^{1/3} = K_e\,(R / W^{1/3})^{A_e}$

Bubble Period: $T / W^{1/3} = K_b / Z^{5/6}$

The coefficients (K) and the exponents (A) are different for each explosive.

In the equations:

P = Peak shock overpressure (psi)

I = Specific shock impulse (psi-sec)

E = Energy flux density (in-lb/sq-in)

T = Bubble period (sec)

Z = Charge depth + 33 (ft)

R = Range (ft)

W = Charge weight (lb)

Reflection and Refraction

Underwater explosion tests usually involve detonating a charge in water between the surface and the bottom. Often, several pulses are sensed by a gauge in the water some distance from the charge. Many of the pulses can be identified as reflections from boundaries. The pulses observed can be classified according to the paths traversed:

1. Direct Shock–a positive pulse (compression)–travels directly from the detonation to the gauge.

2. Surface Reflection–a negative pulse (tension)–results from reflection of the direct shock at the air/water interface.

3. Bottom Reflection–a positive pulse reflected from the water/mud interface.

4. Multiple Reflections–positive and negative–successive reflections from the surface, the bottom, and other obstacles in the area.

In addition to these pulses, the surface reflected tension wave produces a cavitation layer at the air/water interface. When the cavitation bubbles collapse, an additional positive pulse is propagated toward the gauges.

The platform removal detonations all occurred below the mud interface so that bottom reflected pulses were neither observed or expected. Direct shock pulses were observed–most exhibiting the "cutoff" associated with the arrival of the surface reflected rarefaction (tension) wave. Multiple reflections occurred but were not individually identifiable.

Refraction effects occur when shock propagation speed varies along the ray path followed by the shock between the detonation site and the gauge. These effects are usually evidenced as unusually high- or low-shock pressure amplitudes. For the present series, sound speed measurements in the water near the platform indicated a slow and steady increase with depth. No unusual inversions or anomalies were observed, so shock refraction is not an issue for these tests.

GAUGE POSITIONS

The major reason for NAVSWC participation in the operation was to collect data from which to generate similitude-type equations. These equations are used to predict the output from other similar explosions. The location of each gauge relative to the explosion site must be known since gauge range is the independent variable.

The calculation normally used to determine slant range to a gauge in free water requires measurement of the shock transit time in water between the surface of the (spherical) charge and the gauge. The charges in the present tests were placed beneath the bottom, many were toroidal (none were spherical), and it was not feasible to mount a fiducial gauge <u>on</u> each charge. Therefore, the normal ranging algorithm could not be used with any degree of confidence.

The geometric calculation began with an estimate of the distance along the water surface between the vertical down lines to the charge and to each gauge. The slant range between each gauge and the charge was then calculated using the horizontal range, charge depth beneath the bottom, and the gauge height above the bottom.

The effects of bottom material were ignored in this calculation because the first 4 or 5 feet of bottom material in many parts of the ocean has a porosity between 60 and 80 percent.[5] (Porosity is the ratio of free volume to whole volume in a dry sample of material.) The particle diameters of silty material lie between 1/16 and 1/256 mm; the diameters for fine sand lie between 1/4 and 1/8 mm. Thus, the shock from a severance detonation propagates through a largely water-like material, and the effect of the small solid particles was assumed negligible.

Horizontal Ranges

The gauge line was tied to the platform structure on the side closest to the barge. The tie point was chosen to minimize the possibility of snagging underwater portions of the array on submerged debris or portions of the platform structure. As the barge backed off from the platform, the ambient current pulled the line sideways.

The approximate shape of the curved surface line was reproduced on a scaled freehand drawing of the barge/platform arrangement. A sample sketch is shown in Figure 3-1. The Cartesian coordinates relative to the tie point of each of the floats supporting a gauge down line were read from the drawing.

The horizontal coordinates of the charge relative to the tie point were determined from a platform drawing. These coordinates were used with the horizontal coordinates of each down line to determine the horizontal range from the charge to each down line. The geometry is illustrated in Figure 3-2(a).

Slant Ranges

The horizontal distance between the charge and each gauge line, the charge depth below the mud line, and the height of each gauge above the mud line were used to determine the slant range from the charge to the gauge. The geometry and Pythagorean calculation are illustrated in Figure 3-2(b). Results of two such calculations are listed in Table 3-1.

Caveats

The procedure described above involves a number of assumptions that cannot be avoided, given the nature of the operation. Charge-to-gauge slant ranges are indefinite for the following reasons:

- Charge depths below the mud are uncertain ($\pm$18"?).
- The curvature of the surface float line was estimated.
- The gauges are assumed to hang vertically, directly below their respective surface floats. This assumption ignores the effects of subsurface currents.
- The point to which the gauge line was attached to the platform was chosen arbitrarily; its exact location is not known for any of the shots.
- The length of the tie line to the first gauge line was certain only to within 3 or 4 feet.

As a result of these ambiguities, the magnitude of the uncertainty in the slant range of each gauge is estimated to be a minimum of 5 feet.

DATA REDUCTION

Analog magnetic tape data were reduced and analyzed with the R15 Explosion Effects Program and associated hardware.

Each analog record and its associated calibration signal were digitized at 500 kHz. The digitized voltage-time signals were converted to pressure-time data using the calibration signal amplitudes and the calibration constant for each gauge.

Each identifiable pulse on each record was analyzed by calculating the integral under the pulse until it approached (near) the baseline; the resultant quantity is the impulse that would be delivered to a target struck by the pulse. The energy flux carried by a shock pulse was calculated as the integral of the square of the pressure to the same cutoff time as used for the impulse calculation. It is necessary to divide the integral of the square of the pressure-time by the acoustic impedance of the water in order to determine energy, rather than a value proportional to energy.[2]

Pressure-Time Signals

A schematic rendering of a pressure-time signal is shown in Figure 3-3. Many of the features indicated are seen on records obtained from the platform removal shots; however, many are blurred on the records from the more distant gauges:

- Precursor–appears to originate near the water surface; amplitude and timing are irregular.

- Direct shock–originates from the confined under-bottom explosion; it is transmitted through the steel bottom penetrator and bottom material.

- Surface cutoff–the direct shock reflects at the water/air interface as a rarefaction; its arrival at a gauge produces an abrupt cut off of the decay of the direct shock pulse.

- Miscellaneous pulses:

  - Cavitation closure–due to the closure of the cavitation layer produced by the interaction of the direct shock compression and the reflected rarefaction. Natural water cannot withstand tension exceeding 40 to 60 psi and a layer of vapor bubbles 20 to 25 feet thick is produced near the water/air interface. Closure of this layer produces a pressure pulse which arrives well after the arrival of the direct shock and well before the bubble pulse arrival.

  - Bottom pulses–a shock transmitted through the bottom material is ultimately refracted upward into the water. Such pulses can be expected to arrive at a gauge at any time after the arrival of the direct shock. They are irregularly shaped and occur at irregular times.

  - Bubble pulse–A gas bubble is formed when the explosion ruptures its steel confinement and pushes through the surrounding mud. A pressure pulse is radiated into the surrounding water when this bubble collapses after its initial overexpansion.

VARIABLES

Three parameters that differ among the removal explosions were: location of the open top of the tubular, the size of the explosive charge, and the depth of the charge below the mud line. These could not be varied in a systematic and controlled manner, but their effects are noted as far as possible.

Top of Tubular Member

The tops of most of the severed tubular members extended above the surface of the water. The exceptions were the skirt piles and two of the well conductors: their tops were 20 feet or more below the surface of the water. These tubulars were not cut expressly for the removal operation; all cutting done in connection with the removal operation was done above the water surface, primarily for cost effectiveness and job efficiency.

Charge Size

Charge weights were chosen to ensure severance of the bottom penetrating tubulars, not to provide a range of weights for the present study.

Most of the tubulars were severed with Composition B charges weighing approximately 38 pounds. These charges were used to sever 12 platform leg piles and 8 skirt piles. The charges were roughly toroidal in shape and were detonated at two points–at either end of an inner diameter of the toroid.

Five well casings were severed with 25-pound cylindrical charges (length/diameter = 2/1). These charges were lowered into the hollowed out tubulars and detonated at their upper ends.

One, more heavily constructed, well casing was severed with a 50-pound donut charge. Two attempts were required because the first charge failed to detonate properly.

Charge Depth

By regulation, a platform clearance operation must sever bottom penetrators about 15 feet below the mud line. The 25- and 50-pound charges used in the six well conductors were placed either 18 or 20 feet below the mud line. Of the 38-pound octagonal charges used in the 8 skirt piles and 12 main leg piles, one was placed 8 feet and four were placed 26 feet below the mud line. The remaining 15 charges were placed 16 feet below the mud line. These depth variations were made to assess the effects of depth of burial on the shock output of the explosions. (A waiver was required for the shot fired less than 15 feet below the mud line.)

SHOCK PULSE CHARACTERISTICS

It is difficult to generalize the features of the underwater shock pulses emitted by detonations below the sea bottom. The confinement provided by the bottom material and by the steel/grout tubulars is unknown. In addition, there were an unknown number and type of underwater obstructions and variations in bottom material properties. One general observation is that for the multiple shots–those on which two or more charges were fired at about half-second intervals–no interference between the shot pressure signals was observed.

A broad classification of the platform removal detonations may be made according to the location of the upper end of the tubular member: 10 were terminated below the water surface so that the shock emitted from the tubular member propagated into water, and 16 were terminated above the water surface–releasing a shock into the air. Most of the energy in a shock traveling in air is reflected at the boundary between air and water so that precursor pulses from this source are not anticipated.

The next two chapters of this report present data from air-terminated and underwater-terminated tubulars. The last chapter then summarizes the results of the platform removal monitoring operation.

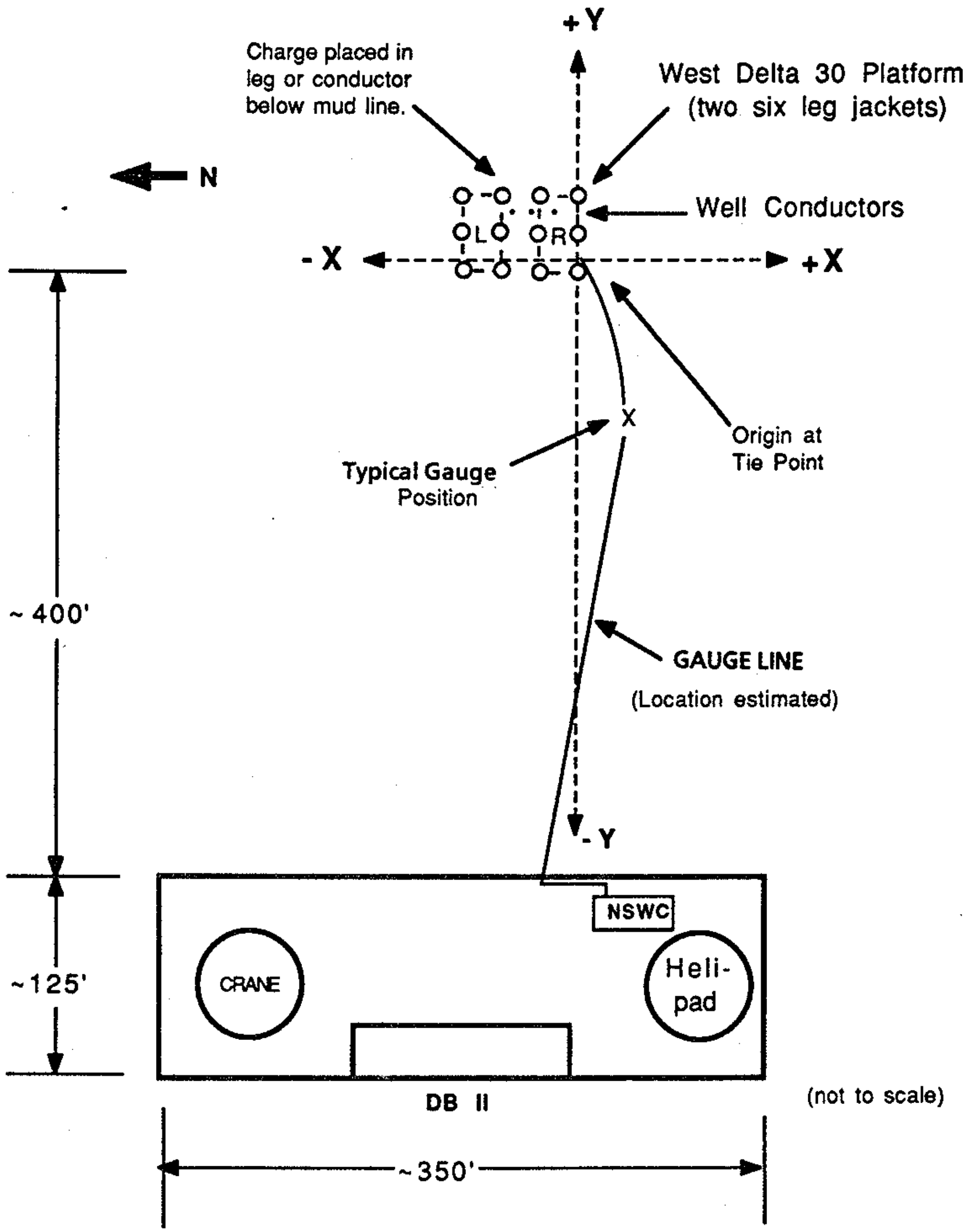
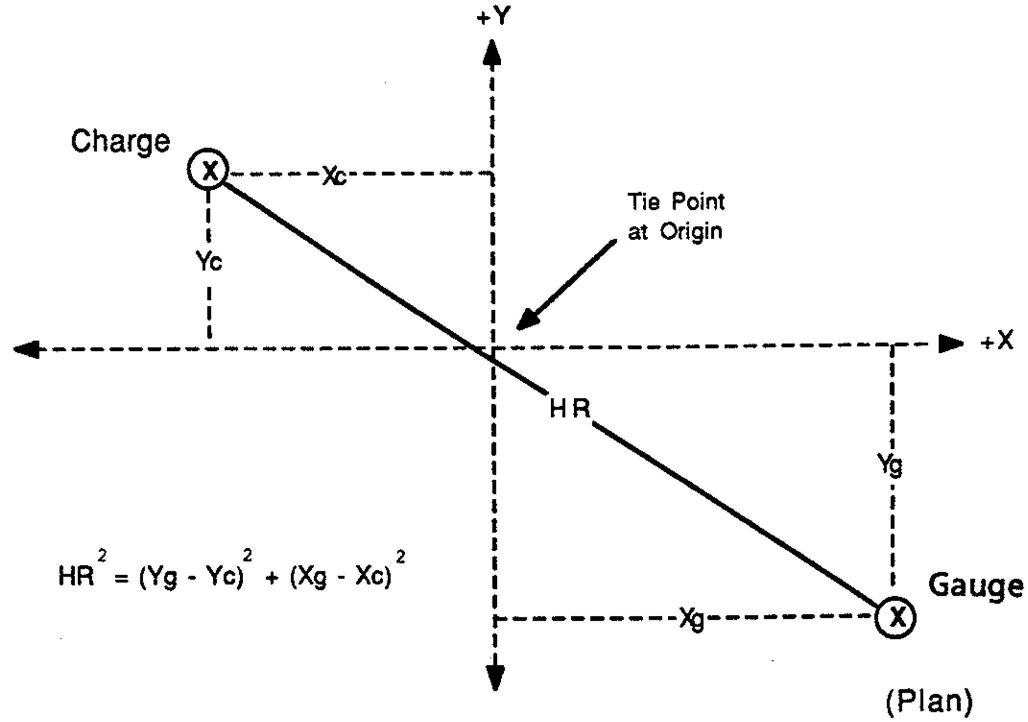
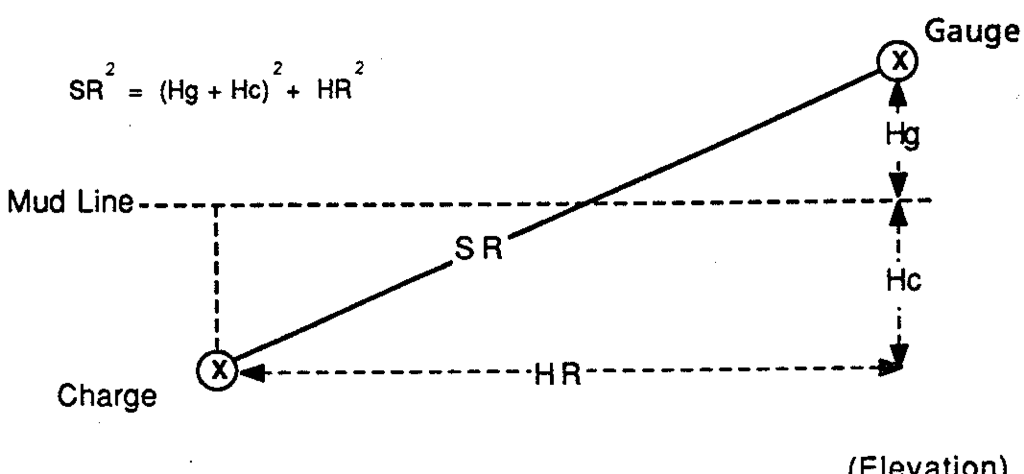


FIGURE 3-1. GAUGE LINE, BARGE, AND PLATFORM GEOMETRY



(a) Horizontal Range Calculation



(b) Slant Range Calculation

FIGURE 3-2. GAUGE RANGE CALCULATIONS

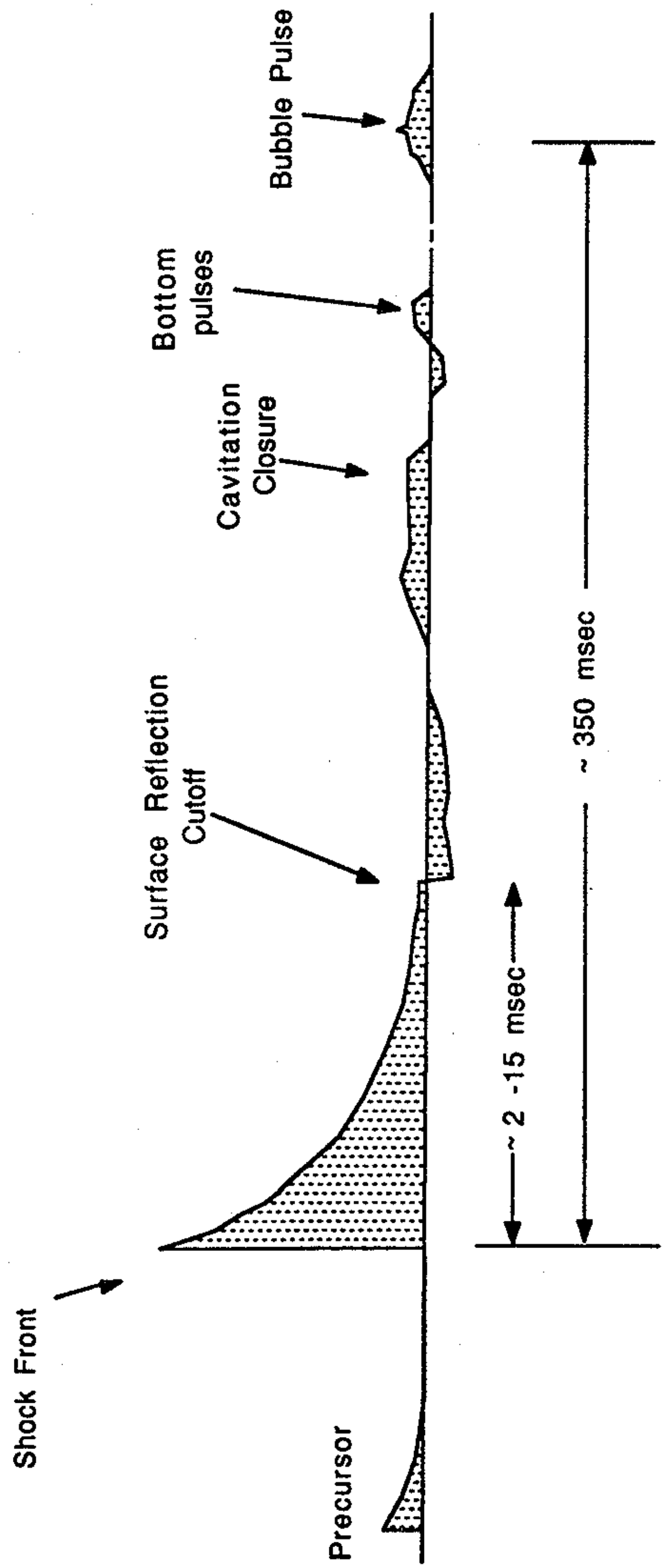


FIGURE 3-3. IDEALIZED UNDERWATER EXPLOSION PRESSURE SIGNATURE

TABLE 3-1. GAUGE RANGING CALCULATIONS

Shot	Gauges	Y chg (ft)	X chg (ft)	Ygauge (ft)	Xgauge (ft)	Horiz Range (ft)	Charge Below Mud (ft)	Gauge Above Mud (ft)	Slant Range (ft)
2876-1	A	6	-33	-4	11	45	20	33	70
	B							18	59
	C							4	51
	D	6	-33	-15	21	58	20	33	79
# 3	E							18	69
	F							4	63
	G	6	-33	-82	50	121	20	33	132
	H							18	127
	I							4	123
	J	6	-33	-275	50	293	20	33	298
	K							18	295
	L							4	294
2876-2	A	6	-49	-4	11	61	20	33	81
	B							18	72
	C							4	65
	D	6	-49	-15	21	73	20	33	90
# 5	E							18	82
	F							4	77
	G	6	-49	-82	50	132	20	33	143
	H							18	138
	I							4	135
	J	6	-49	-275	50	298	20	33	303
	K							18	300
	L							4	299

CHAPTER 4

SHOCK CHARACTERISTICS–AIR TERMINATION

INTRODUCTION

This chapter presents data from 11 of 16 detonations in which the charge was fired in a tubular member whose top end terminated above the water surface. Underwater shock pulses from four well conductor shots and 7 of 12 main jacket pile shots are discussed. The remaining five main pile shots provide no additional information relevant to the analysis.

Free water Pentolite explosion data is used as a comparison standard because a large body of underwater shock wave information on this explosive has been accumulated over the years. Both Composition B and Pentolite are binary mixtures of TNT with another, more sensitive, explosive. (Pentolite is PETN/TNT: 50/50, and Composition B is RDX/TNT: 60/40.) Available data indicate that the underwater shock wave/bubble output from both explosive mixtures is basically the same (Table 4-3 of Reference 6).

On a typical air-terminated platform removal shot record, a single major pulse was observed. The major pulse (interpreted as the direct shock pulse because of the observed surface cutoff dip) was sometimes preceded by a smaller pulse. The pair was followed by a long-duration, low-amplitude negative excursion. Finally, a last pair of pulses (one positive and one negative) appear at a time consistent with the bubble period calculated for a free water Pentolite charge of the same weight. This bubble shock pulse has relatively small pressure amplitude but carries a specific impulse and an energy flux density comparable to those carried by the direct shock pulse. This "late" pulse was not observed consistently on the main pile shots.

WELL CONDUCTORS

Four charges were fired in 20-inch OD conductors that terminated about 10 feet above the water surface. Three were 25-pound cylindrical charges and one was a 50-pound donut shaped charge. Each charge was lowered inside a well conductor to a depth of 20 feet below the mud line. No attempt was made to establish or maintain a particular separation between the charge and the steel wall of the tubular conductor.

Pressure-time Records

Sample pressure-time records for these well conductor shots are shown in Figures 4-1 to 4-5. Identifiable features discussed in Chapter 3 are indicated on each figure.

Figures 4-1 to 4-4 each show various pressure-time records obtained on one pair of the 25-pound well conductor shots. Two conductors were explosively severed less than a half second apart; the top trace in each figure shows the entire record–from before the first detonation to well after the second. The middle trace on each of these figures is an enlargement of the direct shock portion of the first shot. (The second detonation produced a similar record, as did other conductor severance detonations.) The bottom third of each figure shows the late pulse, which can be correlated with the collapse of the explosion gas product bubble.

Figure 4-5 shows the pressure-time records obtained at all three gauge depths at the second station. A precursor appears closer to the direct shock pulse as gauge depth increases. The precursor amplitude decreases at the farther out stations and is sometimes hard to identify.

Similitude Plots

Peak shock overpressure and reduced impulse and energy are displayed as functions of reduced range in Figures 4-6 to 4-11. All have either lower moduli or decay with range at much higher rates than the corresponding free water Pentolite values. (Reduced impulse, energy, and range are calculated by dividing the respective quantities by the cube root of the charge weight in pounds.) This procedure places data from charges of different weights on a common basis.[2] At reduced ranges greater than 100 ft/lb$^{1/3}$ (292 feet for a 25-pound charge, 368 feet for a 50-pound charge), all of the quantities are less than 10 percent of the corresponding archival Pentolite values.

Direct Shock. Figures 4-6 to 4-8 represent the pressure and reduced impulse and energy carried by the direct shock. Each quantity is plotted as a function of reduced range. For comparison, each figure includes a line representing archival free water Pentolite values of the same quantities.

Overpressure and energy values fall below the free water Pentolite line and become insignificant at ranges exceeding 100 ft/lb$^{1/3}$ (292 feet from a 25-pound charge and 368 feet from a 50-pound charge). At close-in ranges, however, impulse (Figure 4-7) approaches an asymptote somewhat above the free water Pentolite line. At greater ranges the shock impulse, like pressure and energy, falls well below the Pentolite line.

This seeming enhancement of impulse is in part due to a difference in integration technique: the Pentolite impulse values were calculated by summing the area under the pressure-time curve for five time constants of the decay of an exponentially decaying pressure-time curve. The calculation for the current shots was extended to the time at which surface cutoff occurred. This is a somewhat greater integration time than used in free water experiments.

The four 25-pound shots and the 50-pound shot are represented by different symbols on these figures. The least squares line was fitted to all the data points for each parameter since there is no distinct difference between the data for the two charge weights.

Bubble Shock. Figures 4-9 to 4-11 are similitude plots of reduced data for the "late" pulse–which can be interpreted as originating in the explosion bubble collapse.

Overpressure and energy are significantly lower than the corresponding Pentolite quantities. Also, both pressure and energy from the 50-pound shot are lower than the same quantities observed on the 25-pound shots. The lower values from the 50-pound shot are probably due to the heavier confinement provided by the particular well casing rather than to a charge size effect. After all, an empirical judgment was made by the explosives contractor to use a larger charge for this conductor because of its construction. A least squares line was fitted to the 25-pound data only and is shown on the figures.

In Figure 4-10 impulse values approach an asymptote somewhat above the free water Pentolite direct shock line at the close-in ranges. Impulse values are equivalent to those produced by the direct shock and are therefore of potential significance. At greater ranges impulse falls well below archival Pentolite values–as does the direct shock impulse.

Discussion

Precursor Pulse. A precursor does not always appear; when present, it sometimes has about the same amplitude as the direct shock pulse, sometimes an amplitude quite small relative to others on the same record, and sometimes it cannot be identified. The amplitude of the precursor on these shots has no evident dependence on gauge depth.

The precursor duration is much less than that of the direct shock immediately following it. In all observed cases, the impulse and energy carried by the precursor pulse is considerably less than that carried by the main shock and the bubble pulses.

The source of the precursor has not been identified–except that it is probably nearer the water surface than the bottom since it appears earlier on the top-most gauge in each vertical string than on the lower gauges in the same string. This is illustrated in Figure 4-5.

Direct Shock Pulses. Direct shock peak pressure, impulse, and energy approach values to be expected from Pentolite at short ranges from the explosions. These parameters are plotted versus reduced (slant) range ($R/W^{1/3}$) in Figures 4-6 to 4-8. Each graph includes the appropriate archival free water Pentolite data for comparison. Slopes of the fitted lines to the well conductor data are steeper than for Pentolite, so that at longer ranges all three parameters rapidly fall away to much less than 10 percent of free water Pentolite values at 300- to 500-foot ranges.

Impulse and energy observed on shallow gauges may be less than the values calculated for free water Pentolite because the direct shock pulses are terminated by the rarefaction reflected from the water surface. This shortening effect becomes less dominant at greater gauge depths. Despite this tendency to shorter pulse length, the impulse data from the well conductor shots is higher at close-in ranges than the Pentolite values for the same ranges and charge weights. The reason for this is not obvious.

Surface Cutoff. The direct shock is reflected from the free water surface as a rarefaction. When the rarefaction reaches a gauge, it abruptly terminates the "smooth" decay of the direct shock pulse toward the baseline. Times observed on the platform removal shots for these cutoffs agree well with values predicted from the charge/gauge geometry–and facilitate the identification of the primary shock pulse amongst the wild gyrations of the pressure recordings. A sampling of surface measured cutoff times is presented in Tables 4-1 and 4-2 together with predictions based on shock speed and gauge and charge depths. The calculation is described in Reference 7.

Bubble Periods. When the gaseous explosion product bubble collapses on itself following its initial overexpansion, a pulse is emitted into the surrounding water. The times after direct shock arrival at a particular gauge at which the "late" pulse occurs are tabulated for four shots in Tables 4-1 and 4-2. These times agree closely with bubble periods calculated for archival Pentolite of the same charge weights. Pentolite bubble periods are also listed in Tables 4-1 and 4-2.

Bubble Pulses. Peak pressure, impulse, and energy from the bubble pulses, though less than the values associated with the direct shock, are still significant. These parameters are plotted versus reduced slant range ($R/W^{1/3}$) in Figures 4-9 to 4-11, together with Pentolite shock data. Peak pressure and energy values fall noticeably below the Pentolite values while impulse matches the Pentolite shock values at close-in ranges. It should be noted that the impulse produced by the bubble pulse is sensibly the same as the direct shock impulse, while the bubble energy and overpressure are definitely less than those produced by the direct shock. All three parameters fall off rapidly with range, becoming insignificant beyond reduced range of 100 $ft/lb^{1/3}$.

Pressure and energy from the 50-pound shots is significantly less than that from the 25-pound shots. (Impulse is indistinguishable between the two.) This apparent charge weight effect probably reflects the fact that the 50-pound charge was used because the well conductor in which it was fired had heavier walls and more reinforcement than the others, in which 25-pound charges were considered (and were) sufficient. The greater confinement attenuated the bubble shock to a greater extent (but extended its duration) than was observed on the 25-pound shots.

Cavitation. Pulses of relatively small amplitude are seen shortly after the direct shock pulse on most records. These probably occur when the surface cavitation layer collapses on itself. This is similar to a water hammer effect. Amplitude and duration of this pulse are small enough that the pulses were not analyzed.

The gauge on cable G (range ~100 feet, depth 20 feet) in all cases produces pressure, impulse, and energy values significantly lower than values observed at surrounding gauges. This is probably because the gauge is in the lower portion of the cavitation layer. The expected depth of the surface cavitation layer is 20 to 25 feet below the water surface at the position of gauge G.

Negative Pressures. Pressure sensed and reported by the gauges became less than ambient at two times on the signatures: immediately following the surface cutoff of the direct shock pulse and immediately following the positive bubble pulse. In both cases, the amplitude was usually about 25 to 30 psi, occasionally reaching 40 to 50 psi. Because natural water tends to break up into cavitation bubbles when subjected to tensions greater than 30 to 50 psi, it is difficult to state unequivocally that the negative pressures reported are really pressures in the water. The values observed are more likely to be the values of pressures in a bubbly cavitated region at the gauge surface. However, these pressures are just those that would be experienced by any solid obstacle in the pressure field around an underwater explosion near enough to the surface to experience surface cutoff.

MAIN PILES

The two West Delta 30 platform jackets each consist of six legs which extend from the sea bottom to 10 feet or more above the water surface. During installation of the jacket, a 30-inch diameter by 1-inch wall thickness pile was driven inside each leg into the mud at the bottom. For the removal operation, mud was scoured from each leg pile to a specific depth beneath the mud line. A 38-pound octagonal Composition B charge was lowered into each pile on the north platform, and the six charges were fired at ~0.5-second intervals. Subsequently, the south jacket was similarly prepared and fired.

Charge depth beneath the mud line was not the same for all the main pile shots. One pile on the north jacket was scoured to allow an 8-foot charge burial depth, and one was scoured to allow a 26-foot depth of charge placement. Enough mud was scoured from the other ten piles on both jackets to allow charge placement at 16 feet below the mud line.

Pressure-time Records

The records from the main pile shots exhibit characteristics similar to those of the records from the well conductor shots discussed in the preceding section. One exception is noted. The "late" pulse on the conductor shots (associated with the explosion gas bubble collapse) was all but invisible on the pile shot records. No analysis of the "late" pulse was attempted because so few examples were found. The lesser prominence of this pulse can be attributed to the relatively thinner walls of the piles providing less restraint to the expansion of the bubble.

Pressure-time records are shown for one of the main pile shots on which the charge burial depth was 16 feet. A complete set of records from one of the four gauge stations is shown in Figures 4-12 to 4-15. The gauge on cable G malfunctioned so its record is not included on Figure 4-14.

Similitude Plots

Figures 4-16 to 4-21 are plots of pressure and reduced impulse and energy versus reduced range from five of the main pile shots on which the charge burial depth was 16 feet. Each of the parameters is plotted without regard to gauge depth in Figures 4-16, 4-18, and 4-20, as well as separately, according to gauge depth in Figures 4-17, 4-19, and 4-21. It is seen that the precision of the fitted line (indicated by the correlation coefficient R^2 accompanying each fitted line) increases for the separated plots.

Figures 4-22 and 4-23 are plots of overpressure and reduced impulse versus reduced range for the precursor pulses. Energy values were all insignificant for these pulses. The scatter in the data represented by these two figures renders it unsuitable for sensible analysis.

As on the well conductor shots, it can be seen that the measured parameters decay more rapidly with range than the similar quantities for archival Pentolite. All may be considered negligible beyond about 500 $ft/lb^{1/3}$.

Discussion

Precursor. A precursor is not always seen. When present, it sometimes has about the same amplitude as the direct shock pulse, sometimes an amplitude quite small relative to others on the same record, and sometimes it cannot be identified. For the main pile shots, the amplitude of the precursor falls as gauge depth increases.

When it is present, precursor duration is less than 20 percent of the duration of the direct shock immediately following it. Impulse and energy in the precursor pulse are less than that carried by the direct shock because the duration of the precursor pulse is so much shorter than that of the direct shock pulse.

The source of the precursor has not been identified--except that it is probably nearer the water surface than the bottom since it appears earlier on the top-most gauge in each vertical string than on the lower gauges in the same string. This is illustrated in Figures 4-12, 4-14, and 4-16.

Direct Shock. Direct shock peak pressure, impulse, and energy approach values to be expected from Pentolite data at short ranges from the explosions. These parameters are plotted versus reduced (slant) range ($R/W^{1/3}$) in Figures 4-16 to 4-21. Each graph includes the appropriate archival free water Pentolite data for comparison. Slopes of the lines fitted to the well conductor data are steeper than for Pentolite, so that at longer ranges all three parameters rapidly fall away to much less than 10 percent of free water Pentolite values at 300- to 500-foot ranges.

Pressure, impulse, and energy behavior for these shots are similar to the same parameters observed on the well conductor shots described in the preceding section.

Surface Cutoff. As was the case for the well conductor shots discussed above, the direct shock pulses on these main pile shots were terminated and became negative at (readily) observable times. The cutoff times agree closely with estimates from geometrical calculations. Observed values are listed in Table 4-3 for shots fired at all three burial depths. Also listed in the table are the geometrical predictions.

Cavitation. Pulses of relatively small amplitude are seen shortly after the direct shock pulse on most records. These pulses probably occur when the surface cavitation layer collapses on itself; it is a water hammer effect, similar to the thump sometimes heard when a water faucet is closed suddenly. Amplitudes of these pulses were considered insufficient ($= <$ 40 psi, in general) to warrant analysis.

Negative Pressures. As on the well conductor shots discussed above, the main pile detonations developed negative pressures after surface cutoff that seldom fell below -40 psi.

Charge Burial Depth Comparison

Figures 4-24 through 4-27 present pressure gauge signals observed on the 8-foot burial depth shots. Figures 4-28 through 4-31 present pressure gauge signals observed on the 26-foot burial depth shots. Following these, Figures 4-32, 4-33, and 4-34 are plots of pressure and reduced impulse and energy versus reduced range for these shots together with the same parameters and the fitted lines for the 16-foot burial depth shots.

Comparison of Figures 4-24 through 4-31 with Figures 4-12 through 4-15 indicates that the signals from the 8- and 26-foot burial depth shots are at least qualitatively similar to those produced by the 16-foot burial depth shots. The records from the 16- and 26-foot burial depth shots are cleaner than those from the 8-foot burial depth shots. The precursor and direct shock pulses on the deeper shots are clearly distinguishable; this is not so on the 8-foot shot records.

The precursors on the 8-foot shots (when they could be identified) occurred closer in time to the direct shock than did the precursors on the 16- and 26-foot shot records.

The amplitudes of the precursors on the 16-foot shot records were lower at the greater gauge depths. In contrast, the amplitude of the precursors on the 26-foot shots increased with gauge depth.

The direct shock data from detonations at all three burial depths is indistinguishable. This is shown by the similitude plots in Figures 4-32, 4-33, and 4-34. In these three figures, points are plotted for the 8- and 26-foot burial depths. The points are seen to cluster about the least square lines transferred to these figures from Figures 4-16, 4-18, and 4-20. There is no obvious distinction between the data obtained from shots at the three charge burial depths.

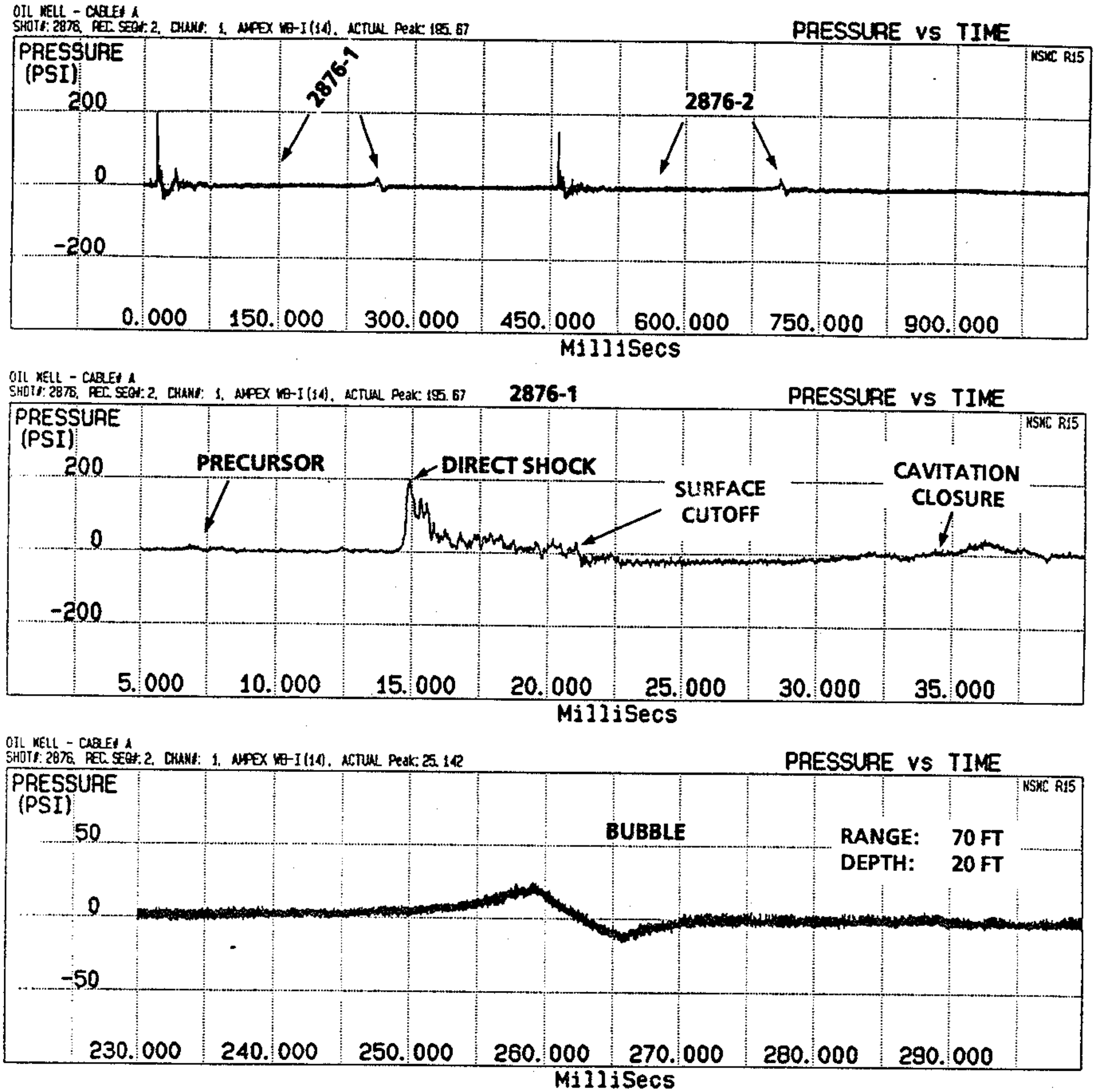


FIGURE 4-1. WELL CONDUCTOR PRESSURE RECORDS
(TOP GAUGE AT FIRST STATION)

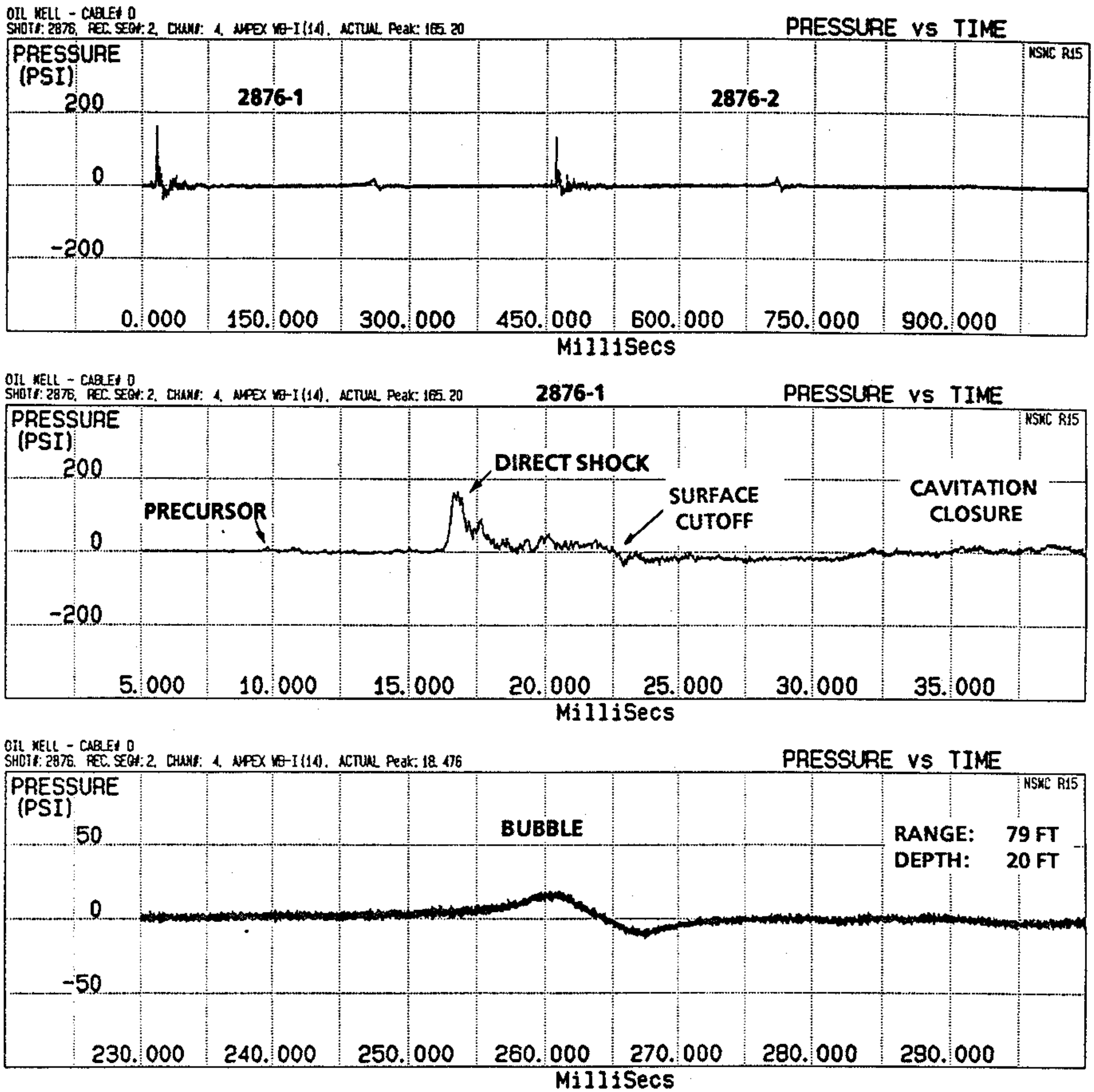
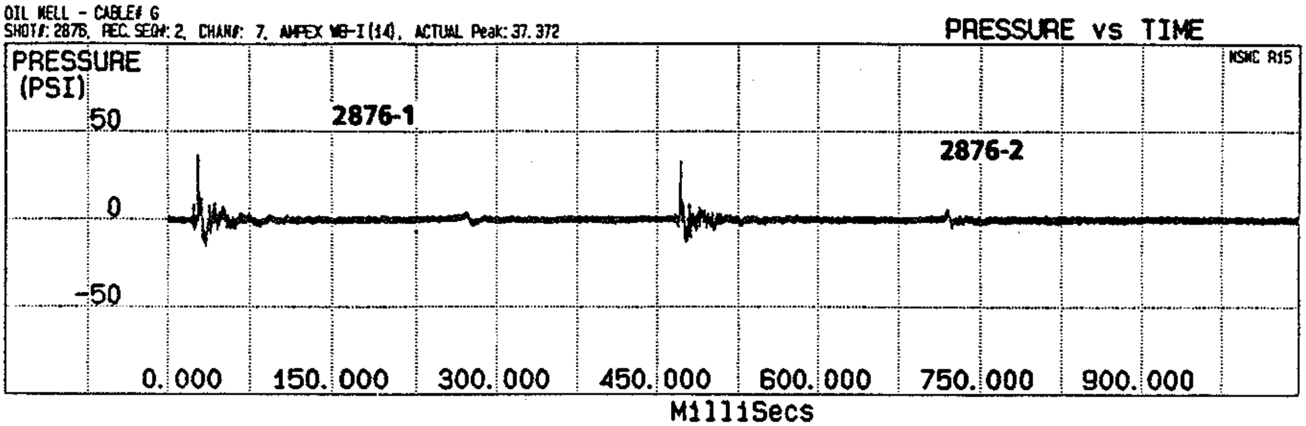
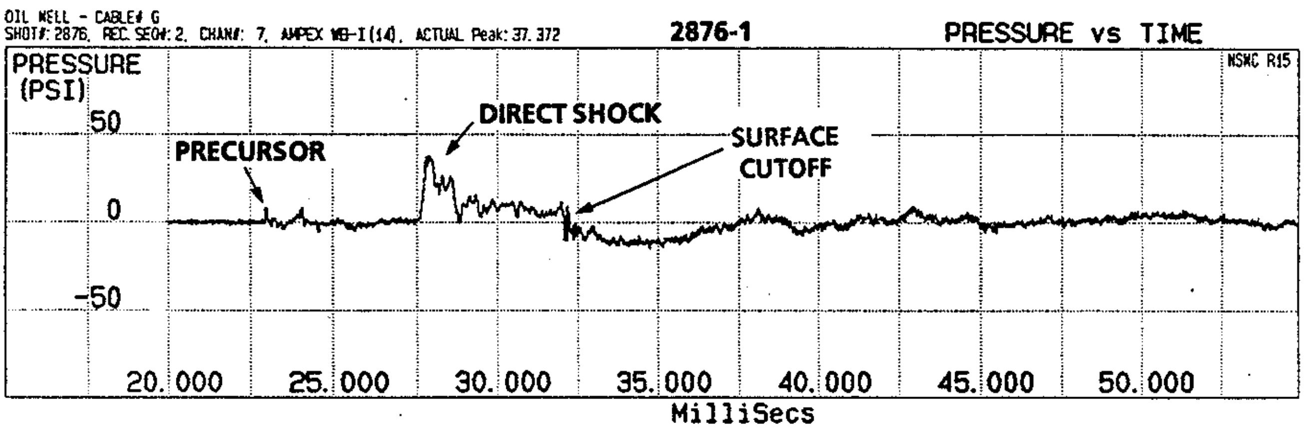


FIGURE 4-2. WELL CONDUCTOR PRESSURE RECORDS
(TOP GAUGE AT SECOND STATION)





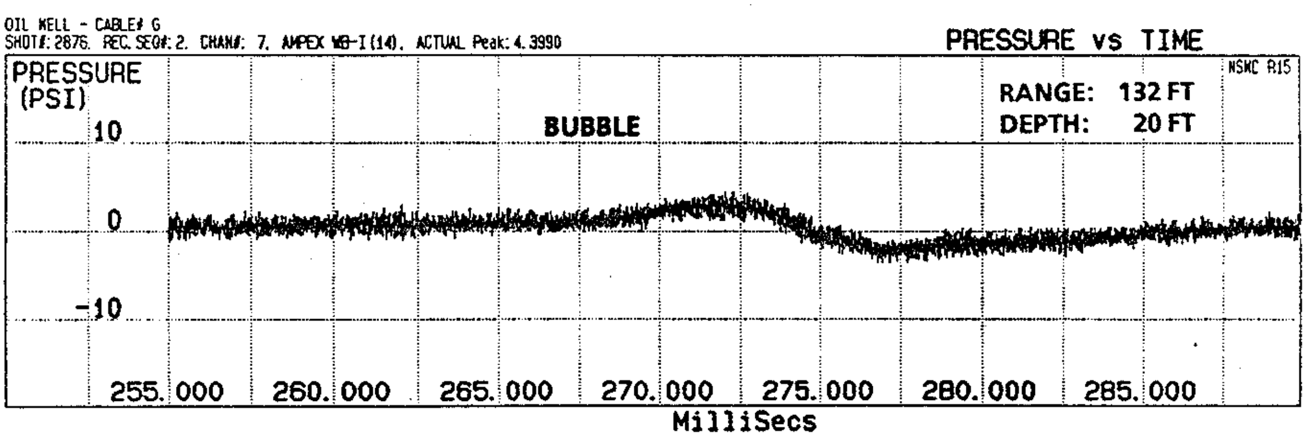


FIGURE 4-3. WELL CONDUCTOR PRESSURE RECORDS
(TOP GAUGE AT THIRD STATION)

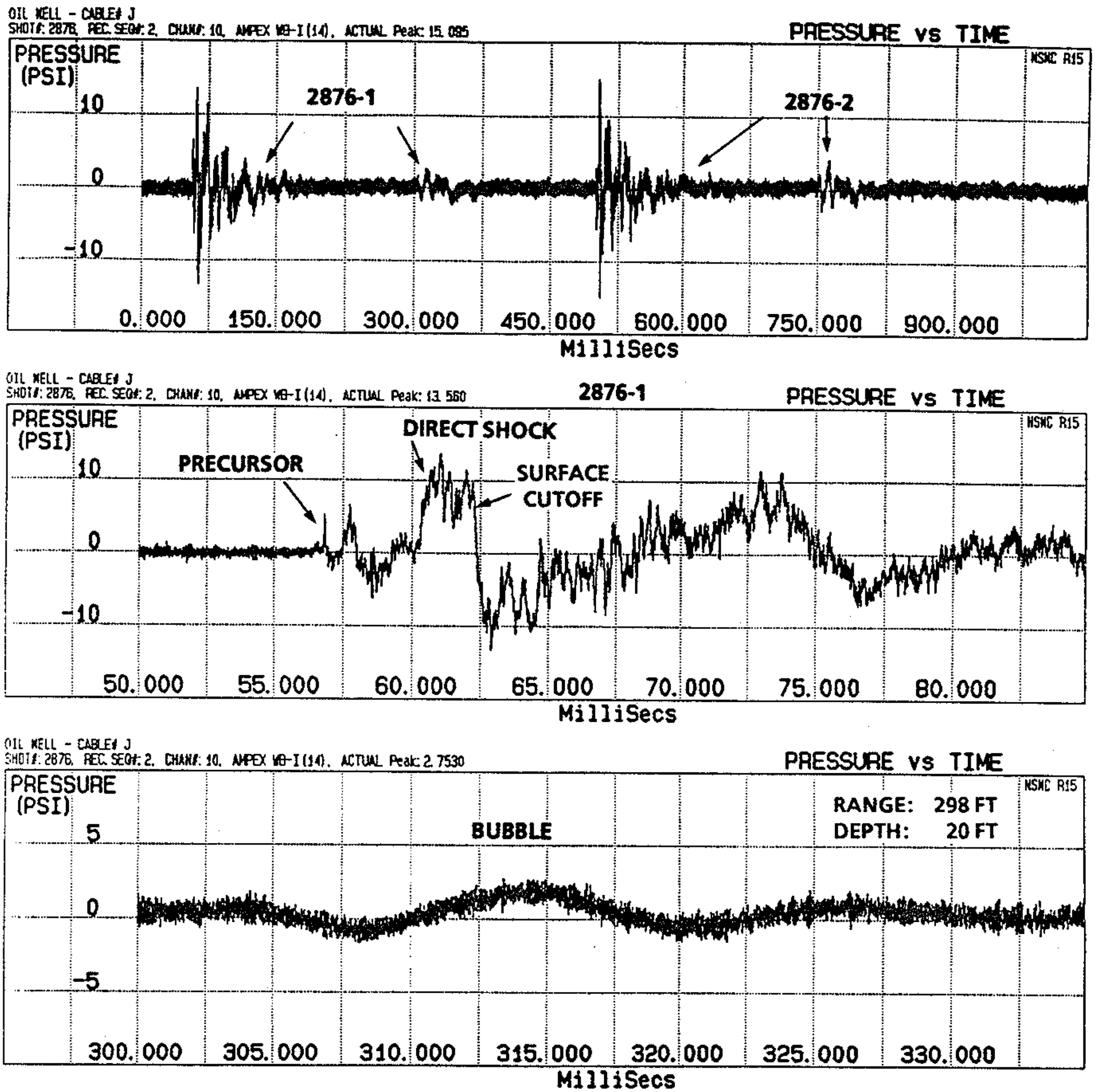


FIGURE 4-4. WELL CONDUCTOR PRESSURE RECORDS
(TOP GAUGE AT FOURTH STATION)

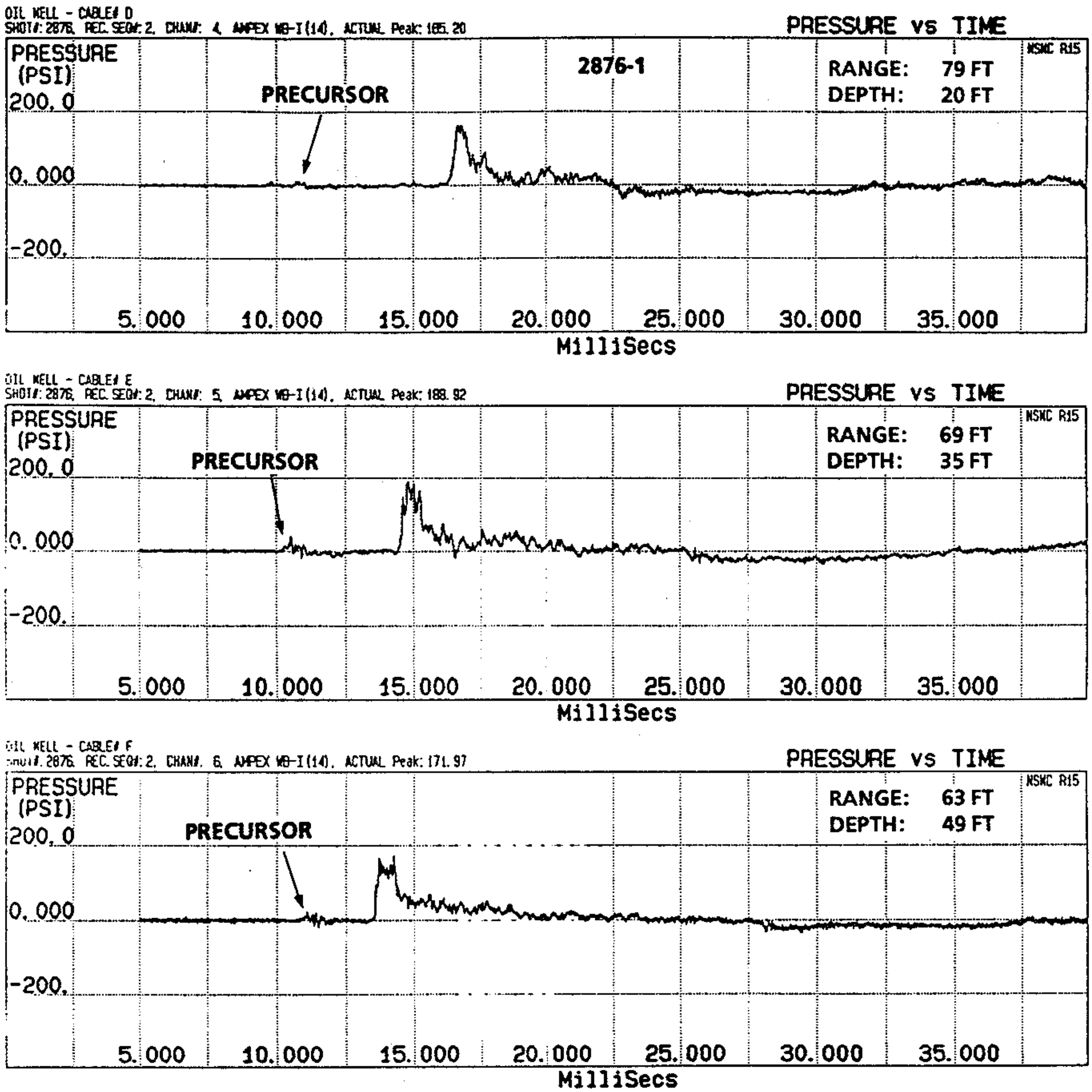


FIGURE 4-5. WELL CONDUCTOR PRESSURE RECORDS (PRECURSOR AT SECOND STATION)

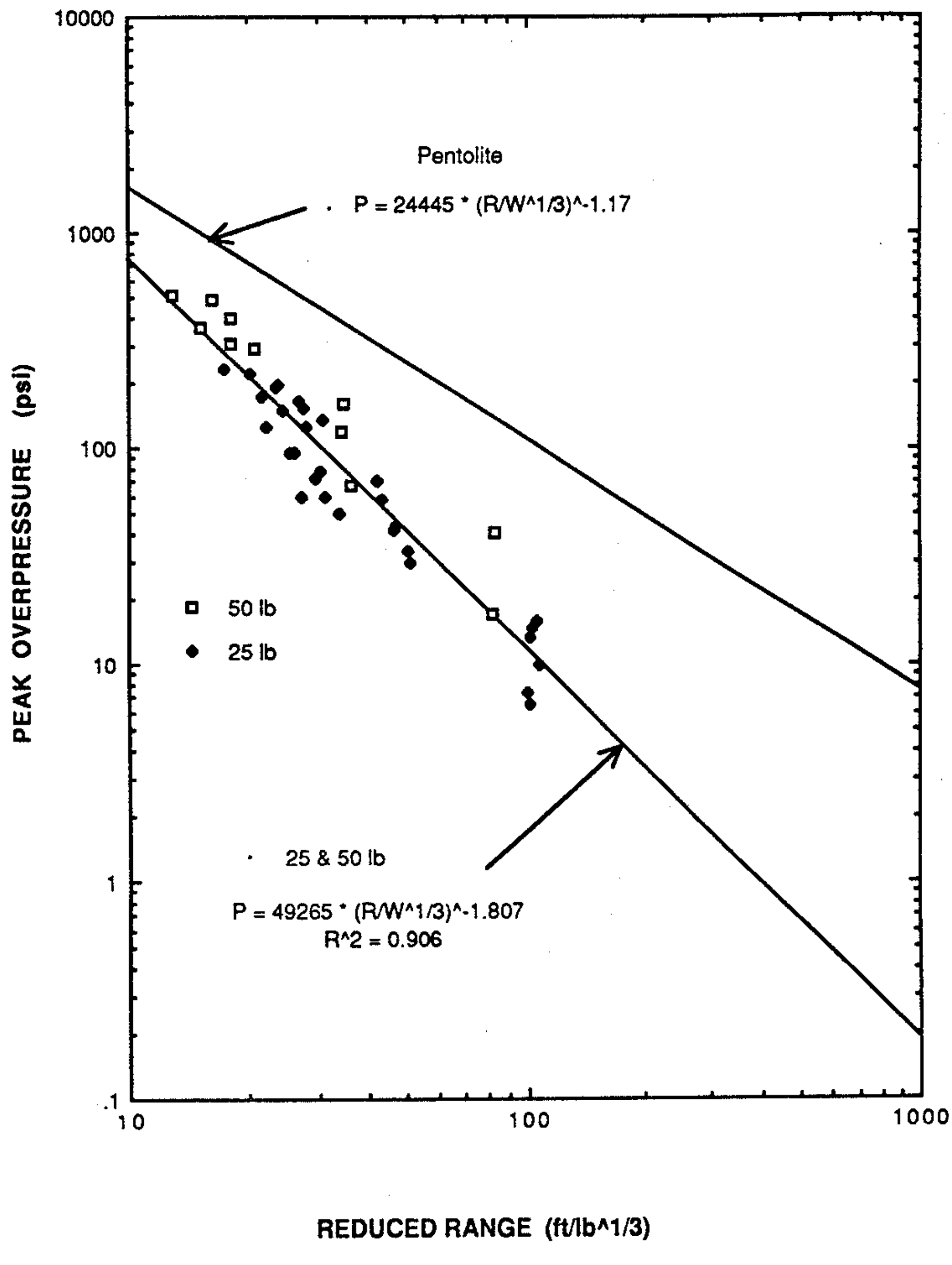


FIGURE 4-6. DIRECT SHOCK OVERPRESSURE FROM WELL CONDUCTORS

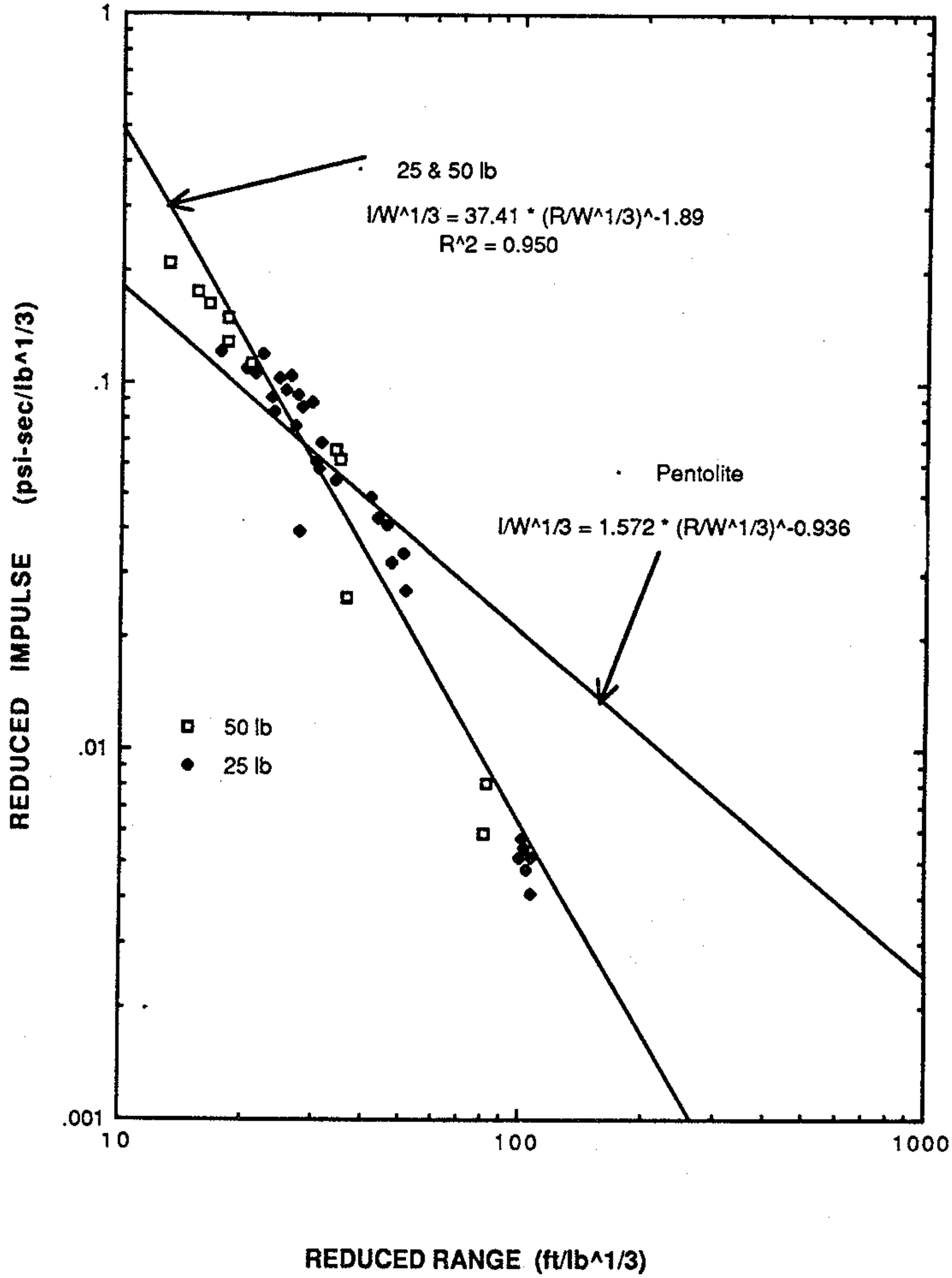


FIGURE 4-7. DIRECT SHOCK IMPULSE FROM WELL CONDUCTORS

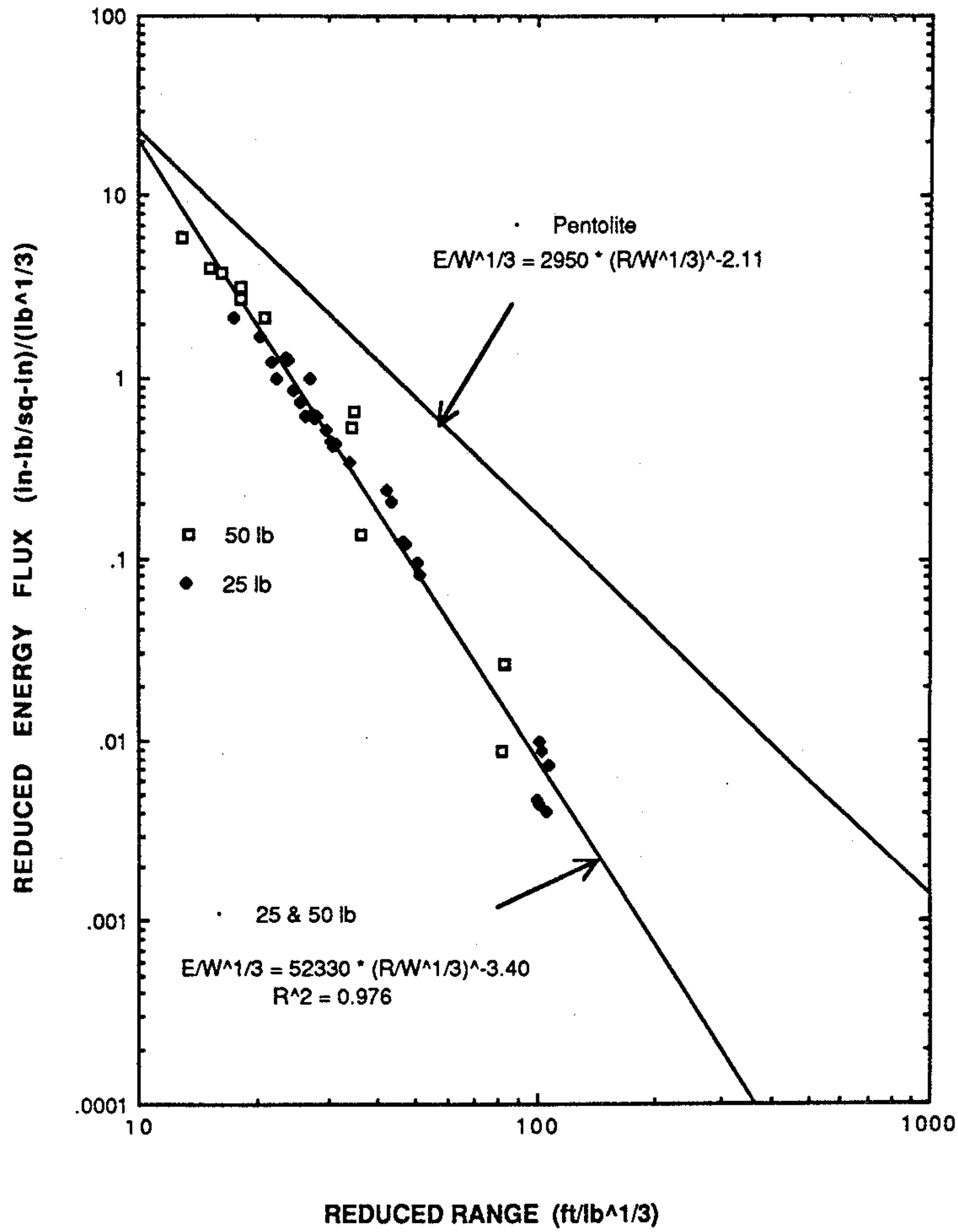


FIGURE 4-8. DIRECT SHOCK ENERGY FROM WELL CONDUCTORS

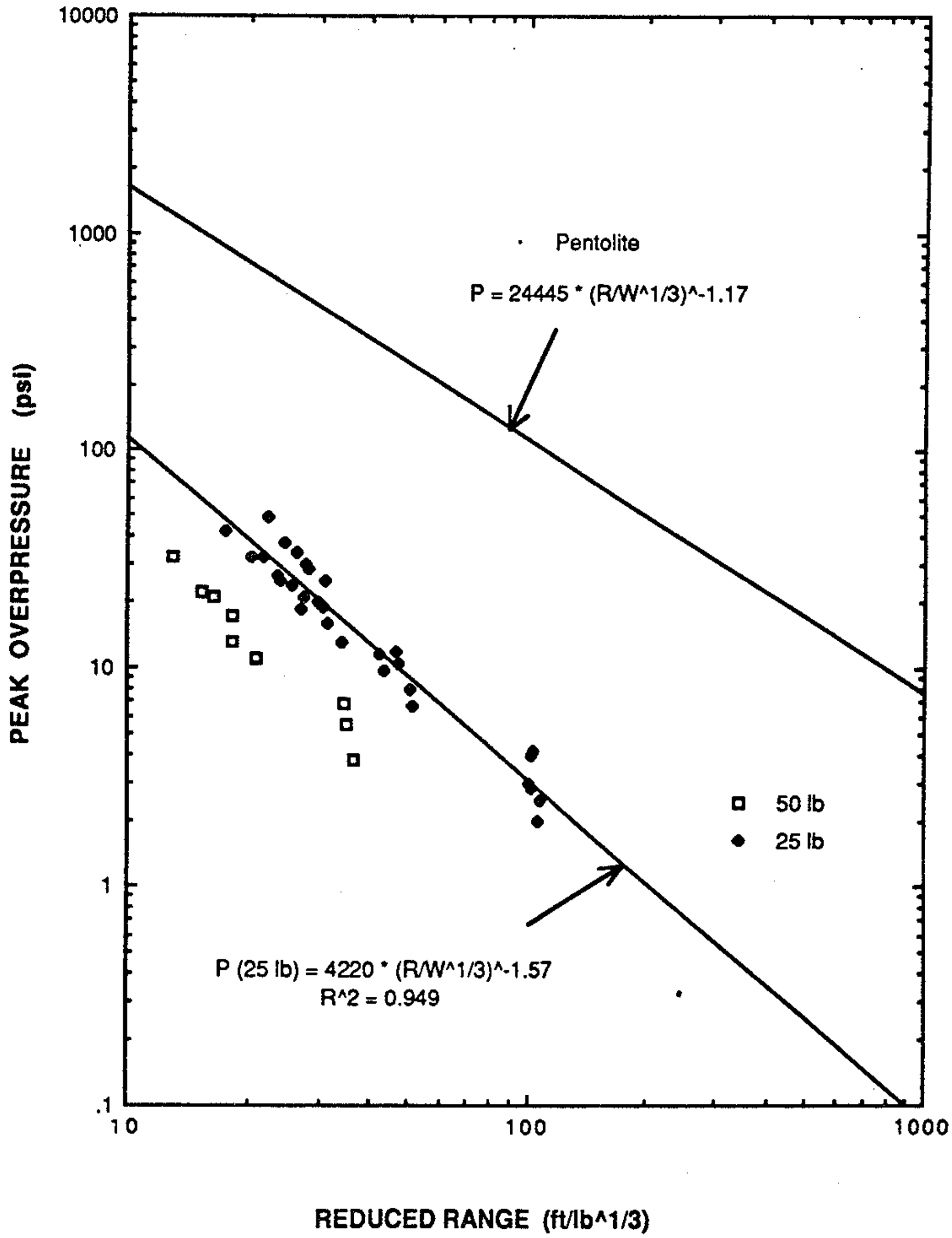


FIGURE 4-9. BUBBLE SHOCK OVERPRESSURE FROM WELL CONDUCTORS

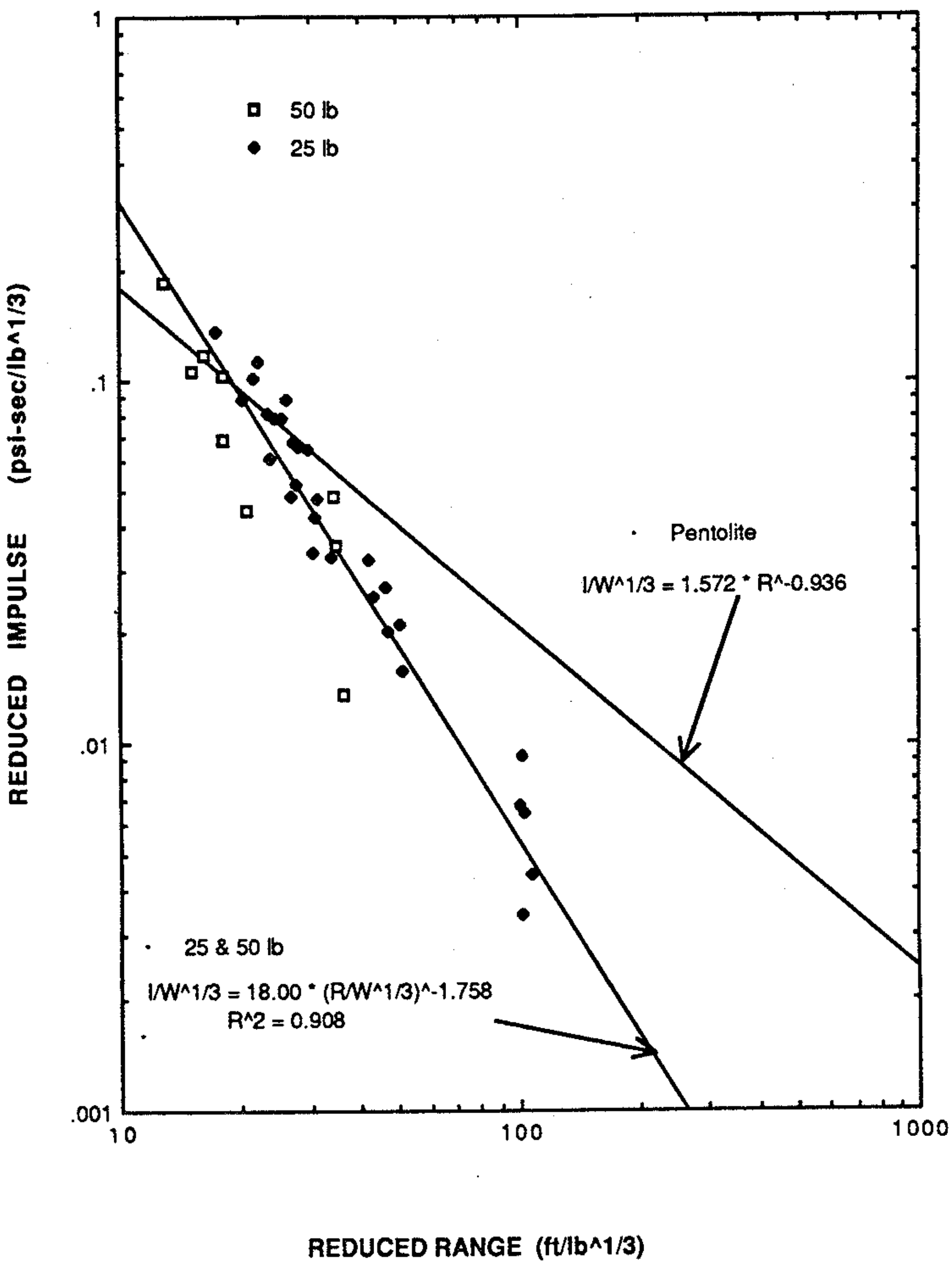


FIGURE 4-10. BUBBLE SHOCK IMPULSE FROM WELL CONDUCTORS

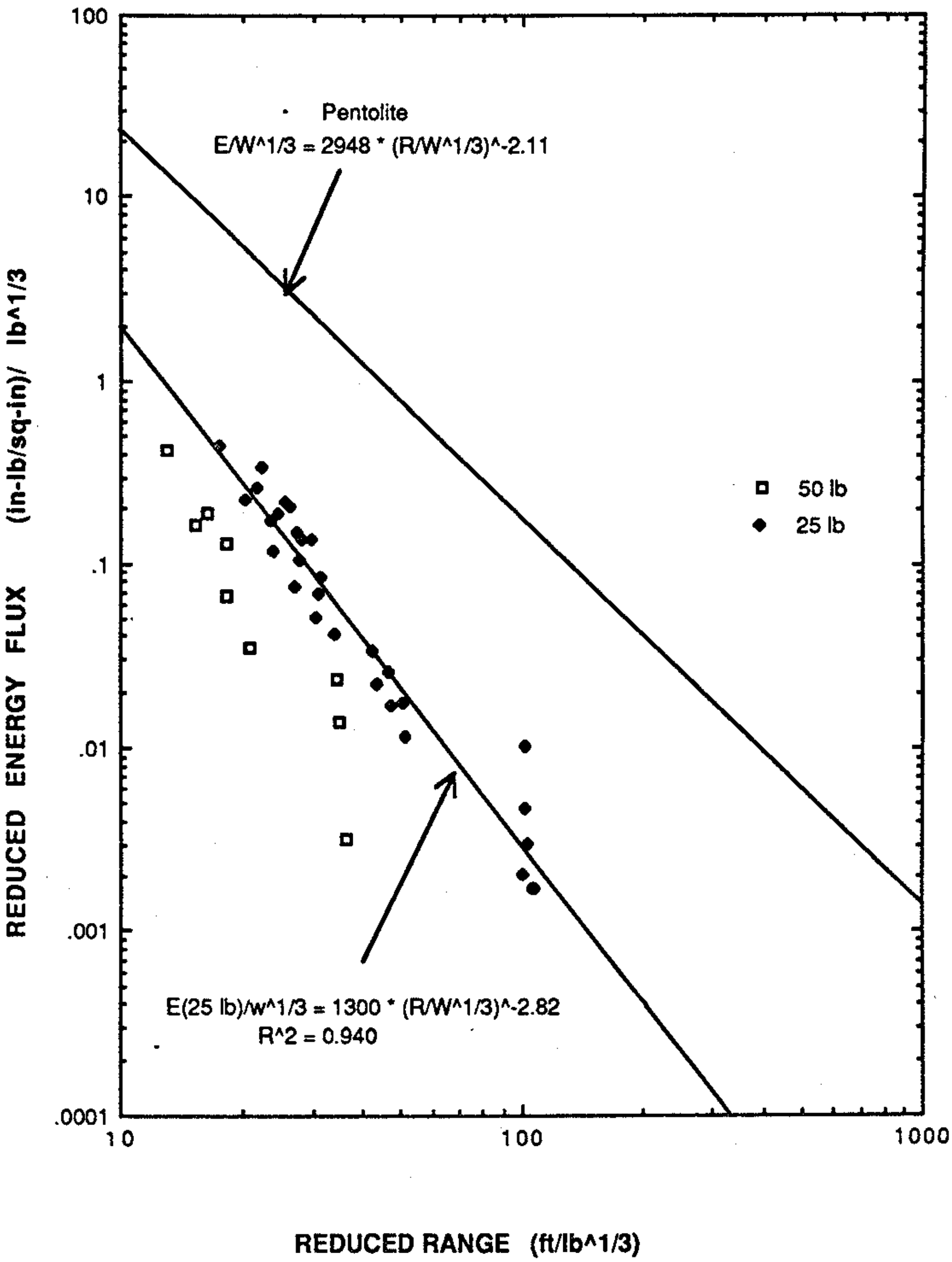


FIGURE 4-11. BUBBLE SHOCK ENERGY FROM WELL CONDUCTORS

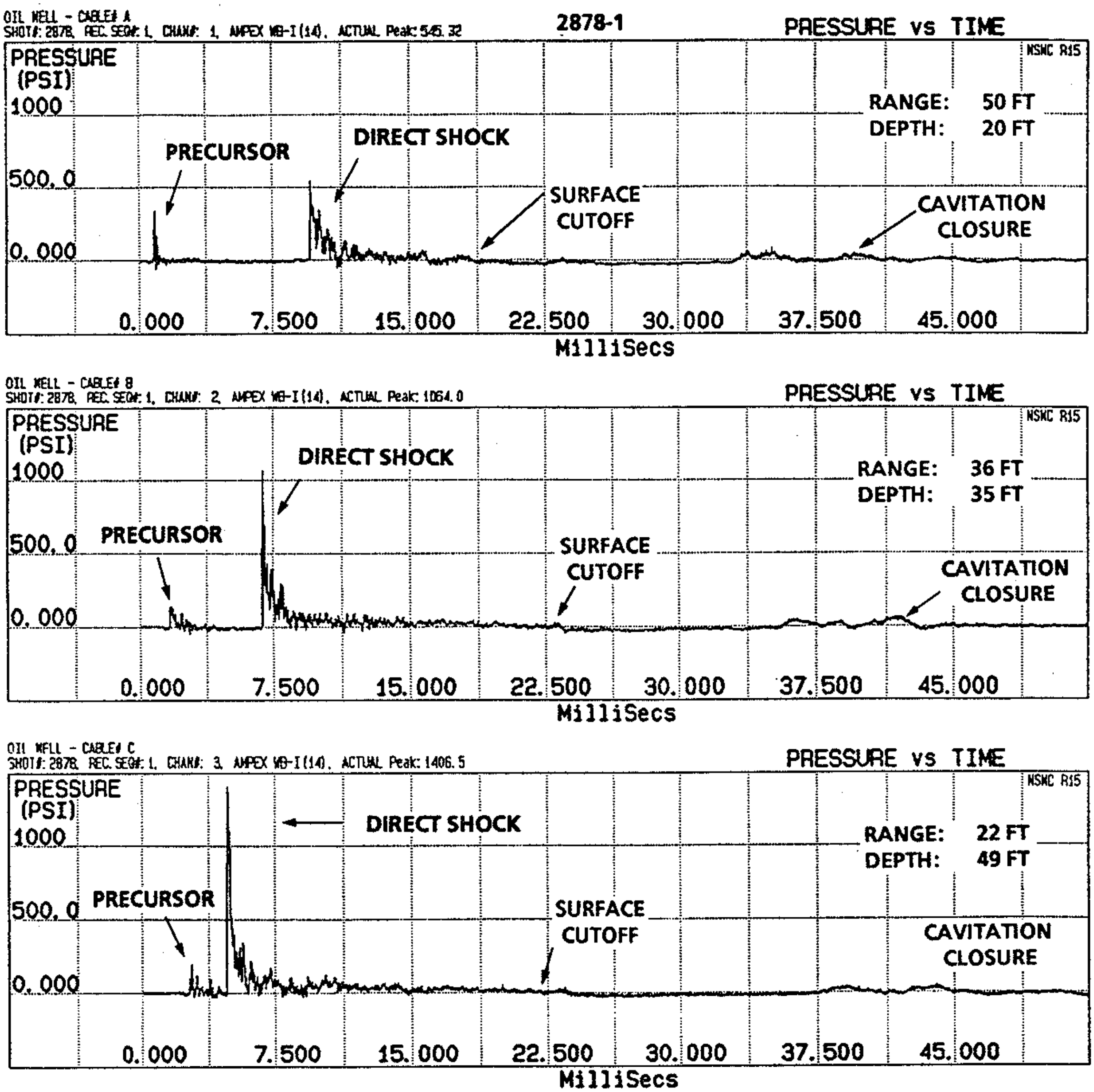


FIGURE 4-12. MAIN PILE PRESSURE RECORDS (FIRST GAUGE STATION)

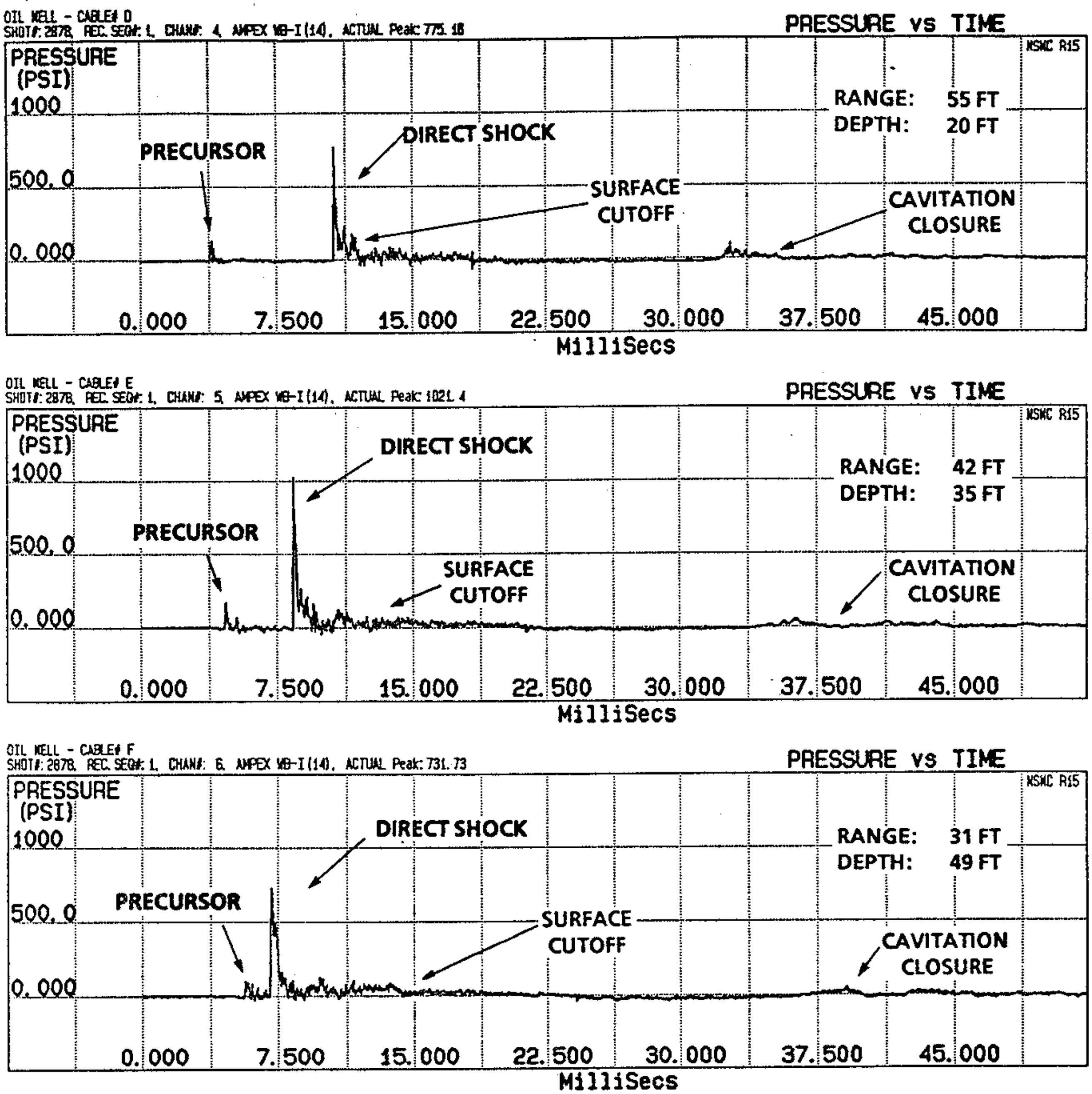


FIGURE 4-13. MAIN PILE PRESSURE RECORDS (SECOND GAUGE STATION)

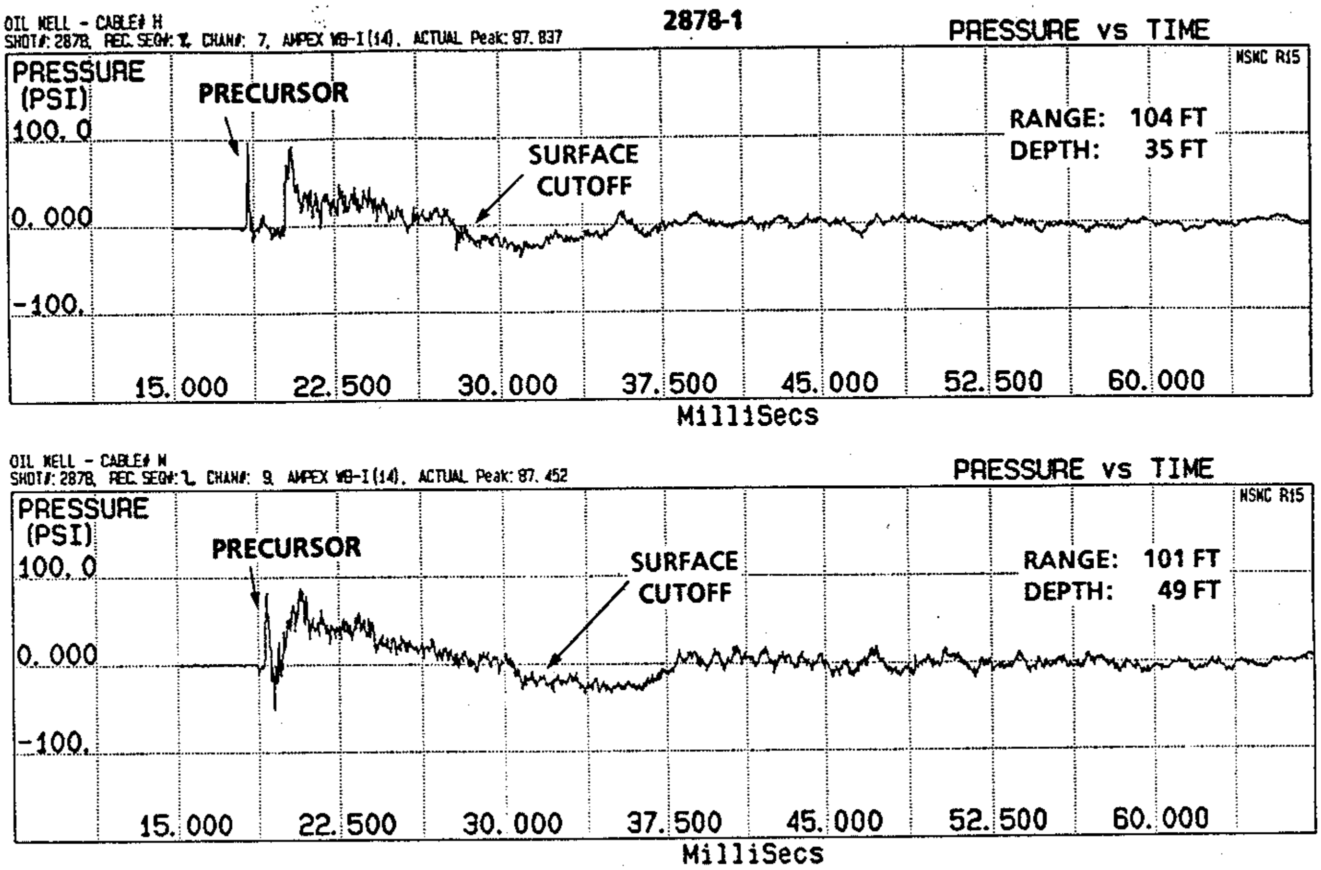


FIGURE 4-14. MAIN PILE PRESSURE RECORDS (16-FOOT DEPTH)
(THIRD GAUGE STATION)

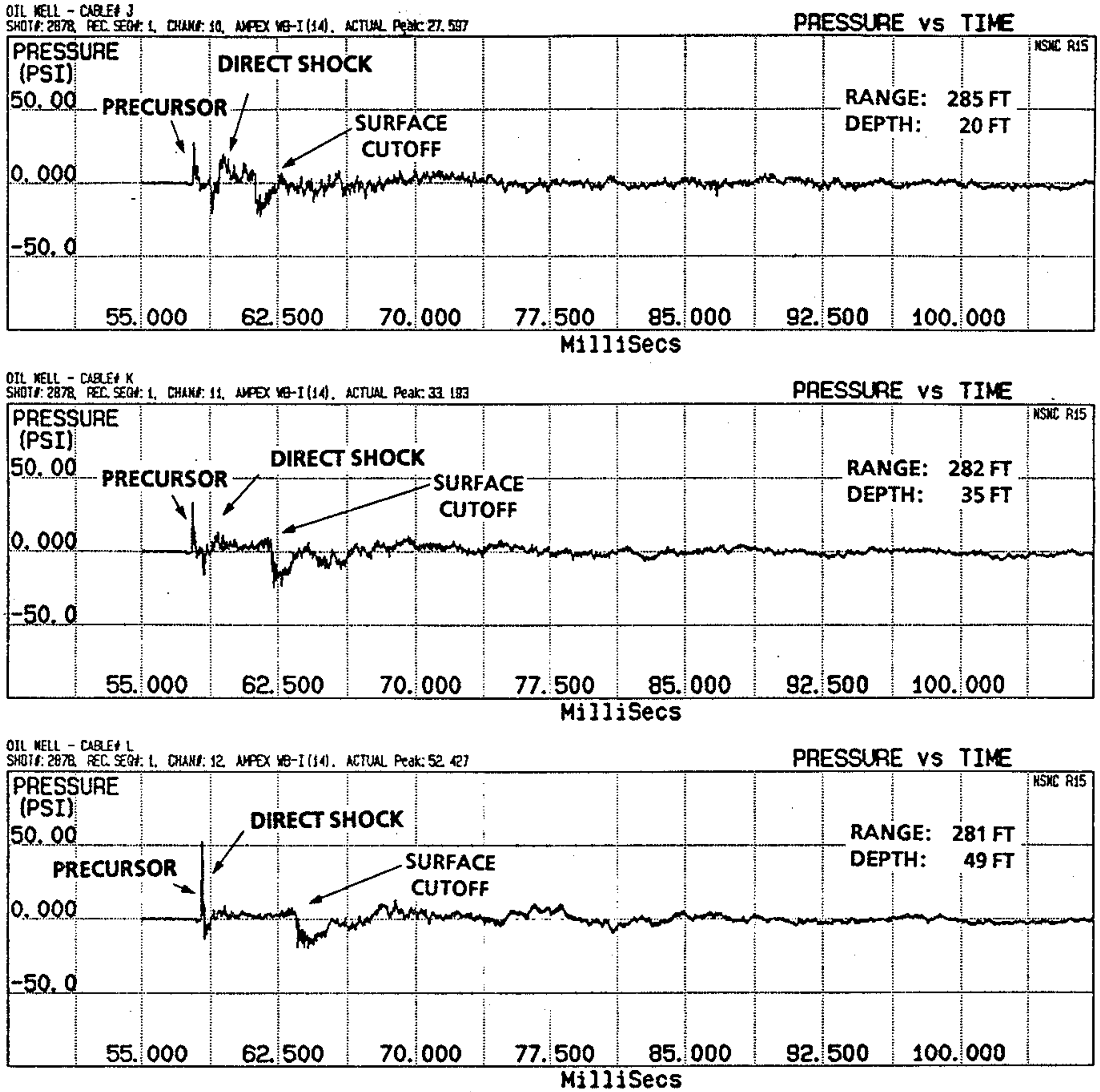


FIGURE 4-15. MAIN PILE PRESSURE RECORDS (FOURTH GAUGE STATION)

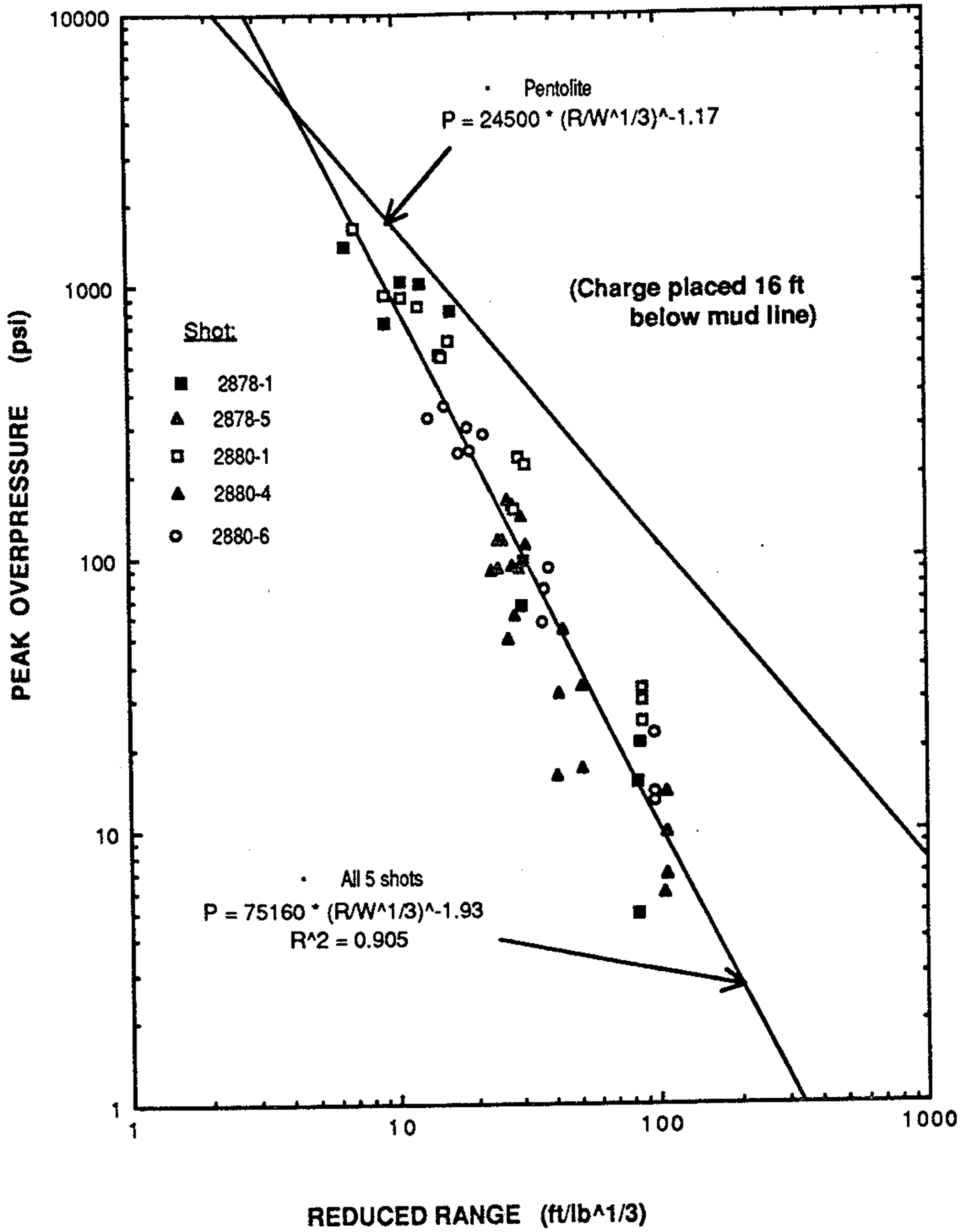
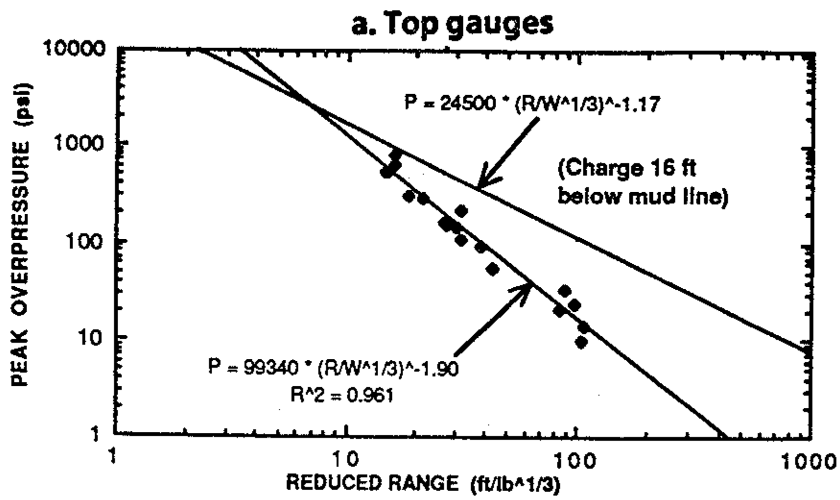
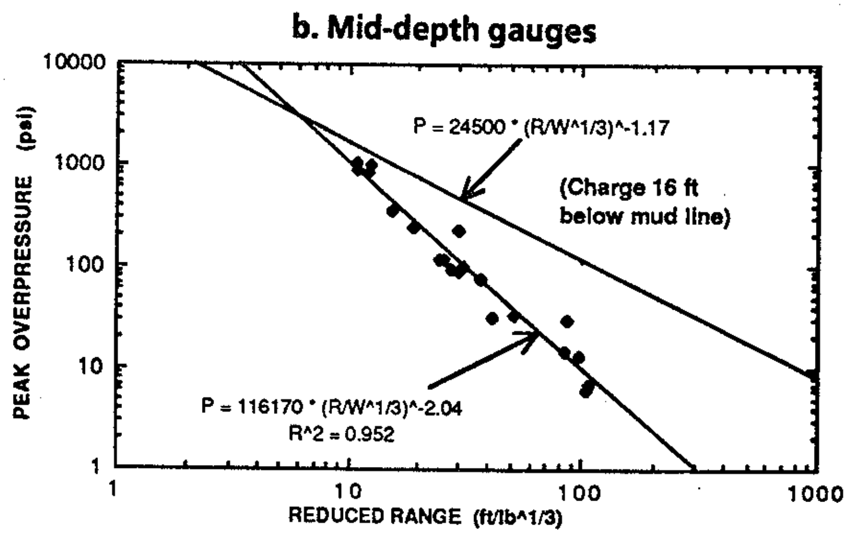


FIGURE 4-16. DIRECT SHOCK OVERPRESSURE FROM MAIN JACKET PILES





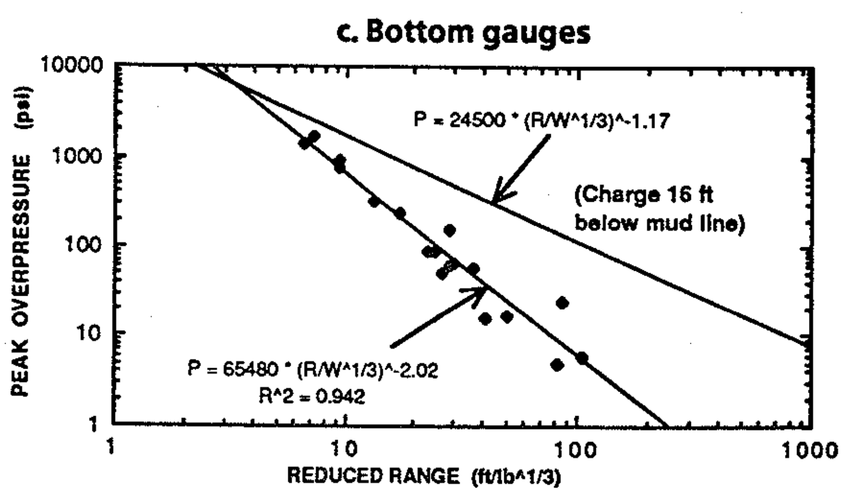


FIGURE 4-17. DIRECT SHOCK OVERPRESSURE FROM MAIN JACKET PILES (TOP, MIDDLE, BOTTOM GAUGES)

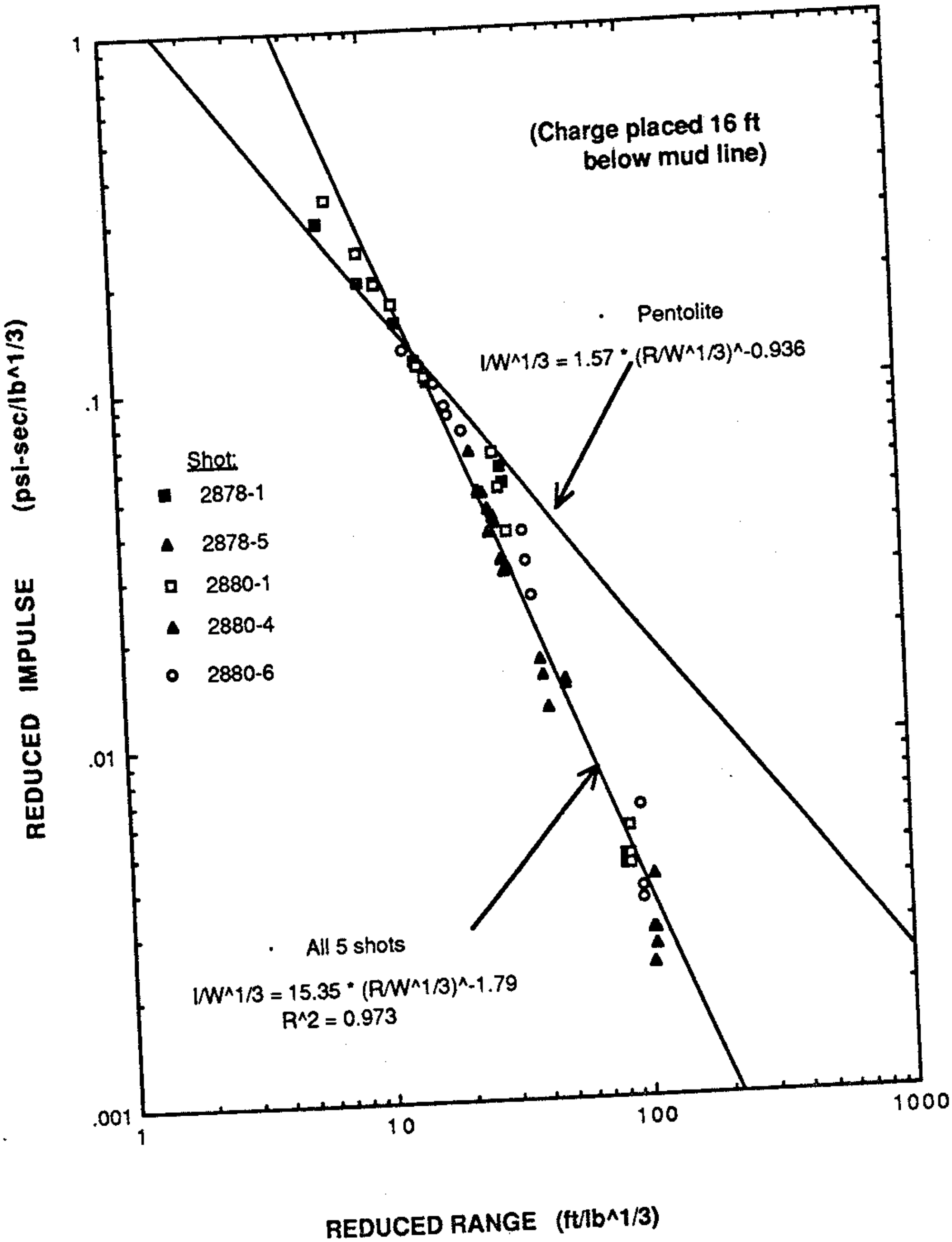
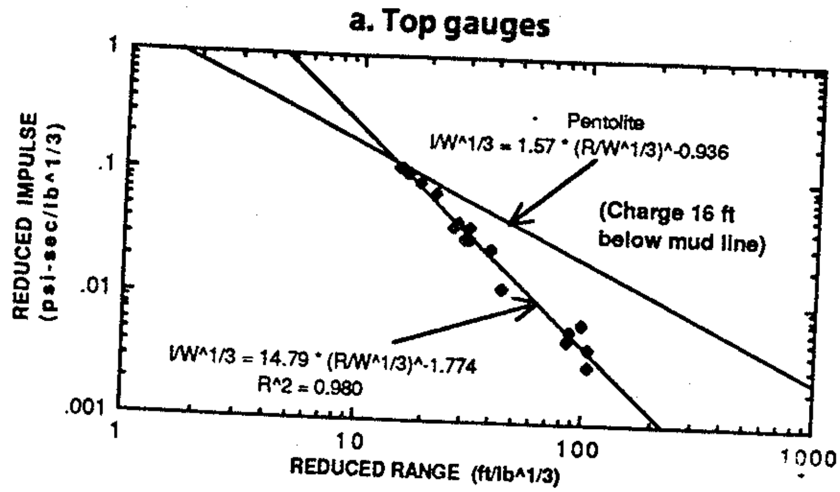
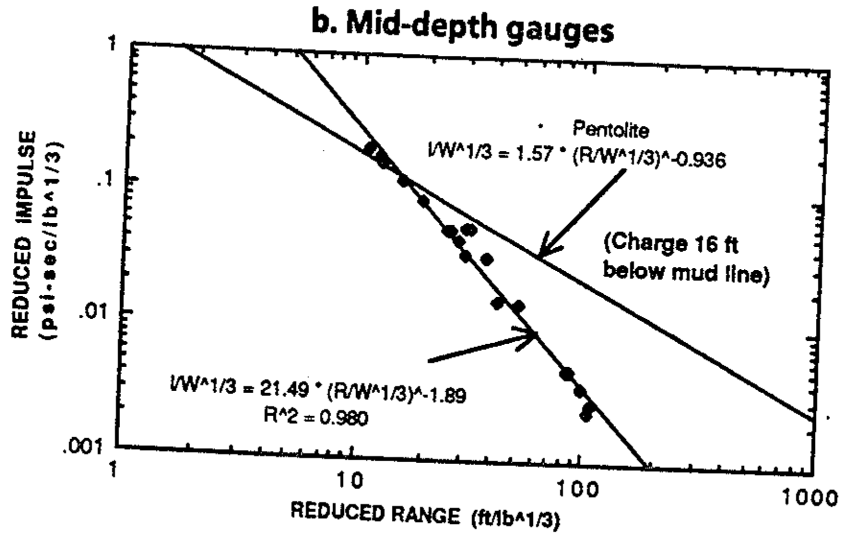


FIGURE 4-18. DIRECT SHOCK IMPULSE FROM MAIN JACKET PILES





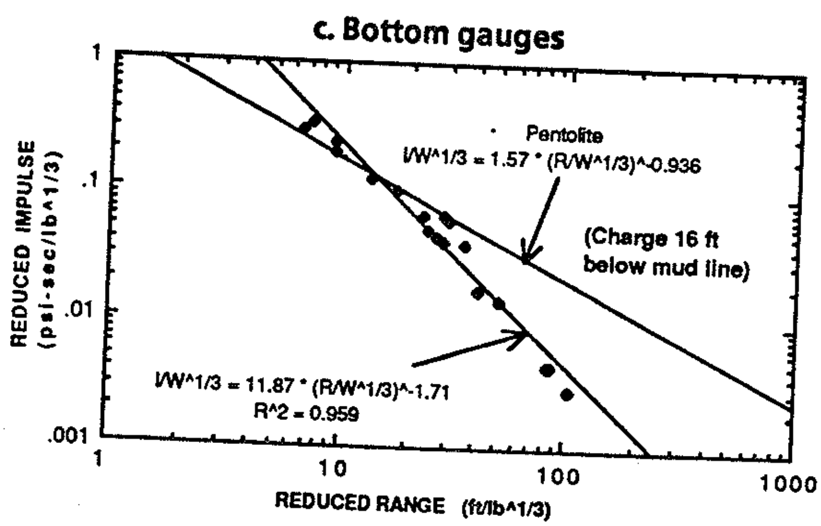


FIGURE 4-19. DIRECT SHOCK IMPULSE FROM MAIN JACKET PILES (TOP, MIDDLE, BOTTOM GAUGES)

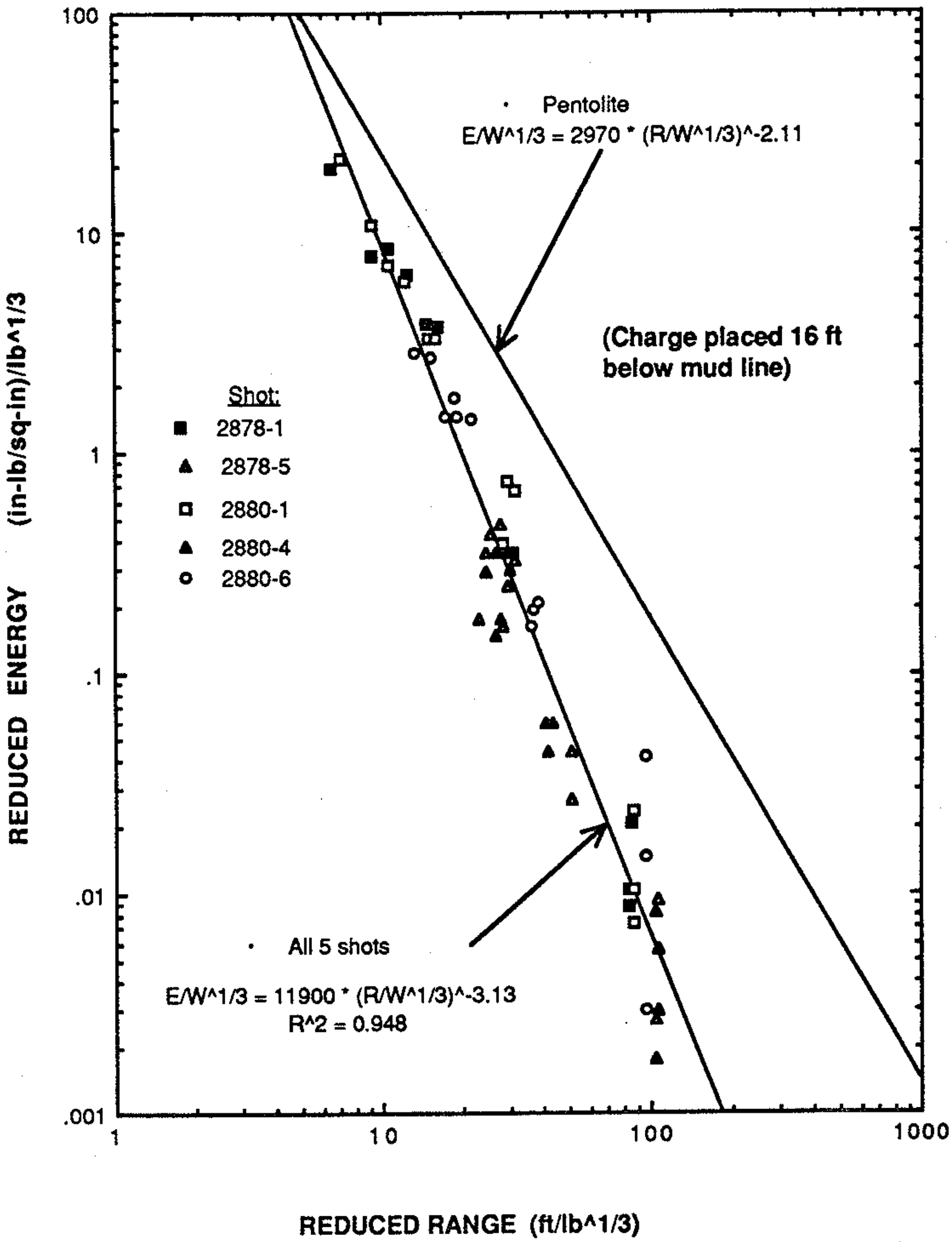


FIGURE 4-20. DIRECT SHOCK ENERGY FROM MAIN JACKET PILES

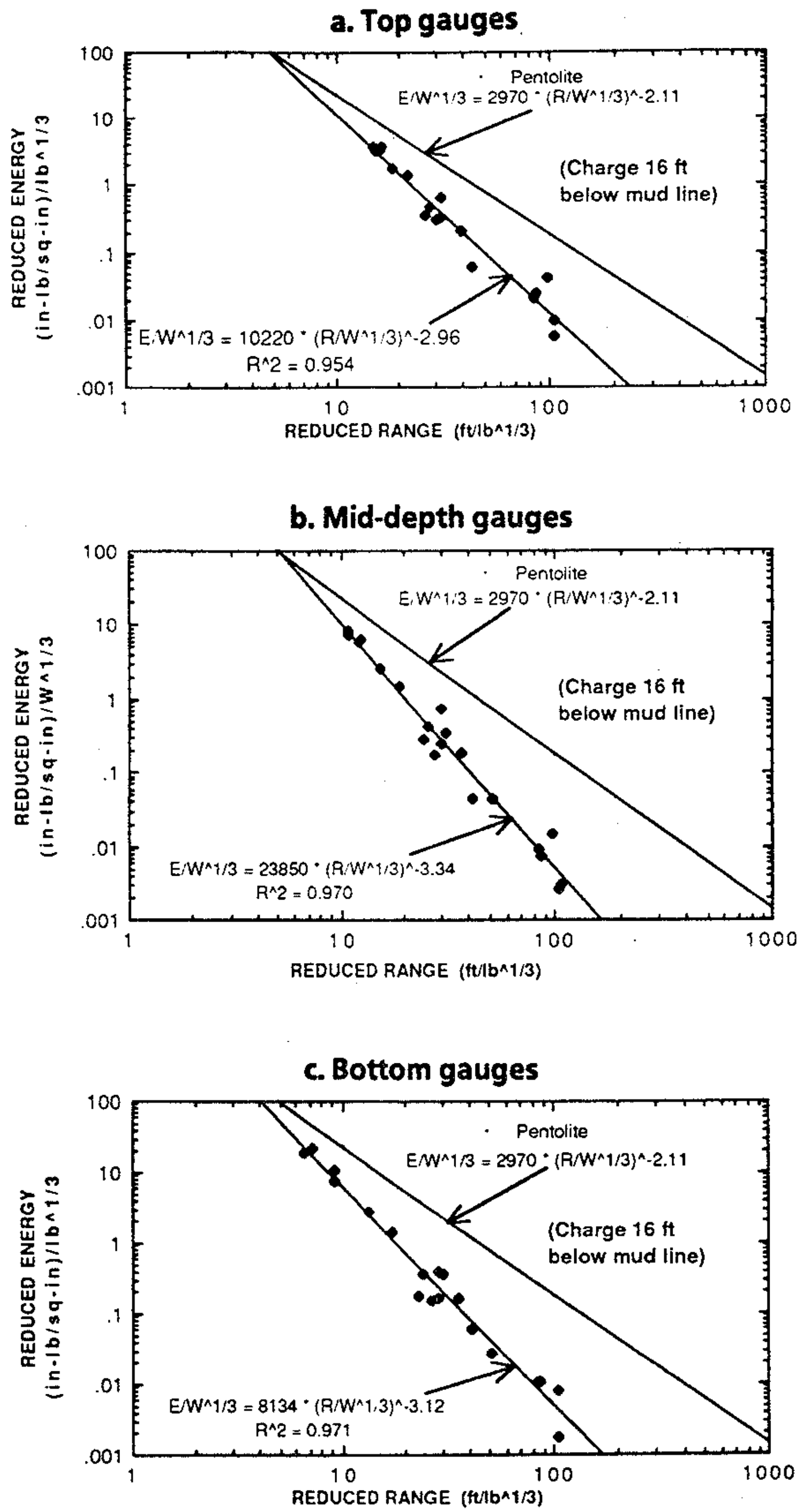


FIGURE 4-21. DIRECT SHOCK ENERGY FROM MAIN JACKET PILES (TOP, MIDDLE, BOTTOM GAUGES)

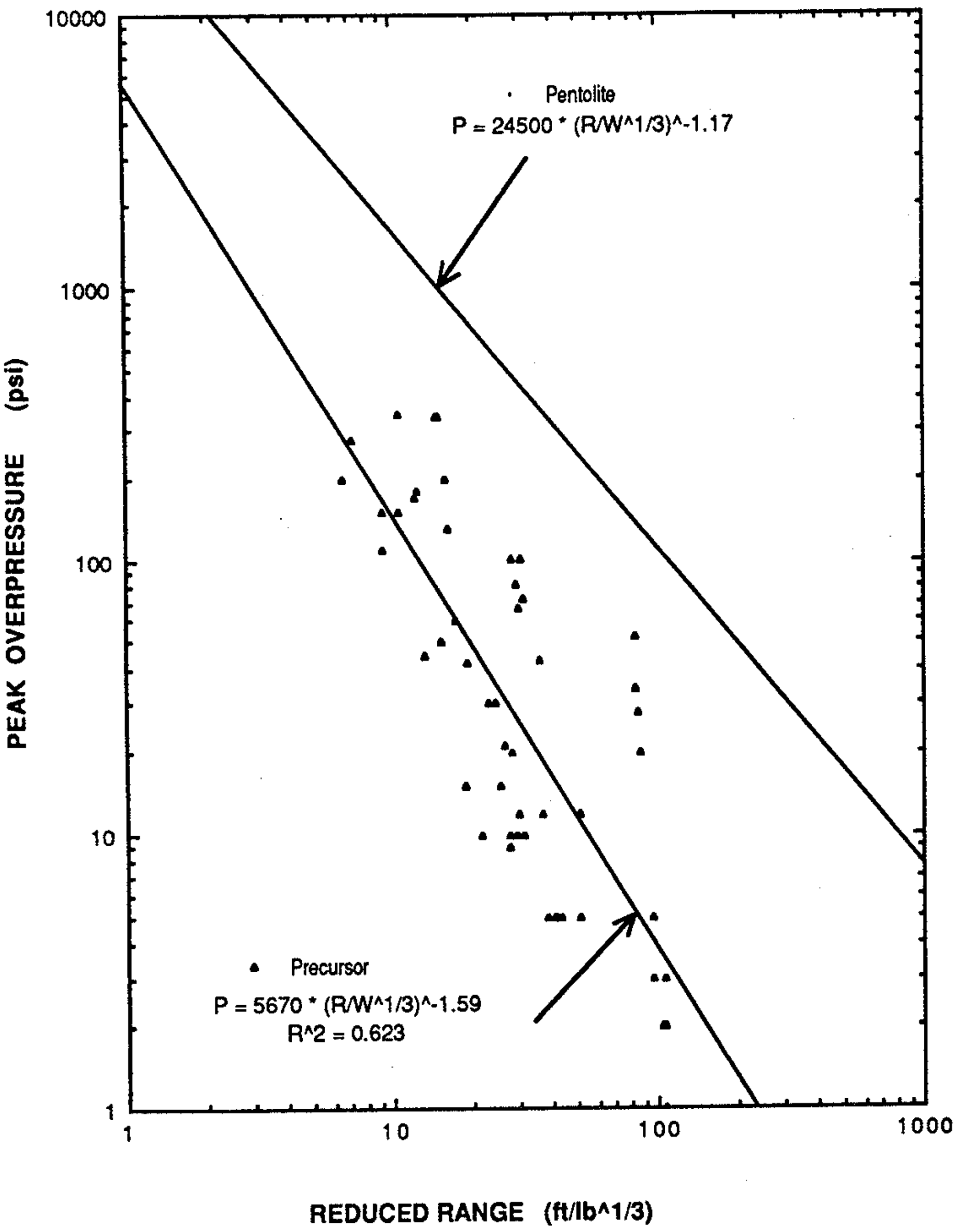


FIGURE 4-22. PRECURSOR SHOCK OVERPRESSURE FROM MAIN JACKET PILES (16-FOOT CHARGE DEPTH)

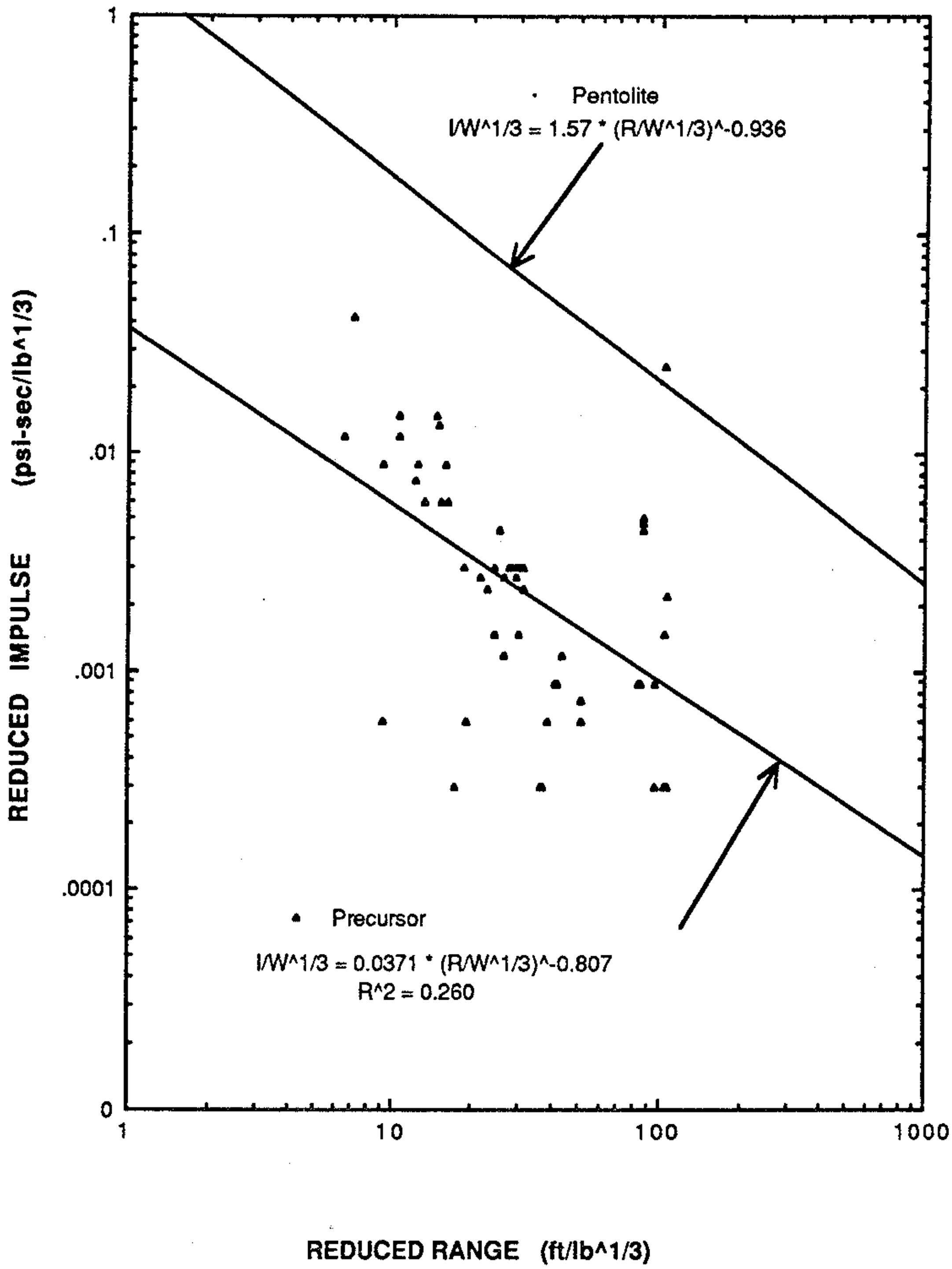
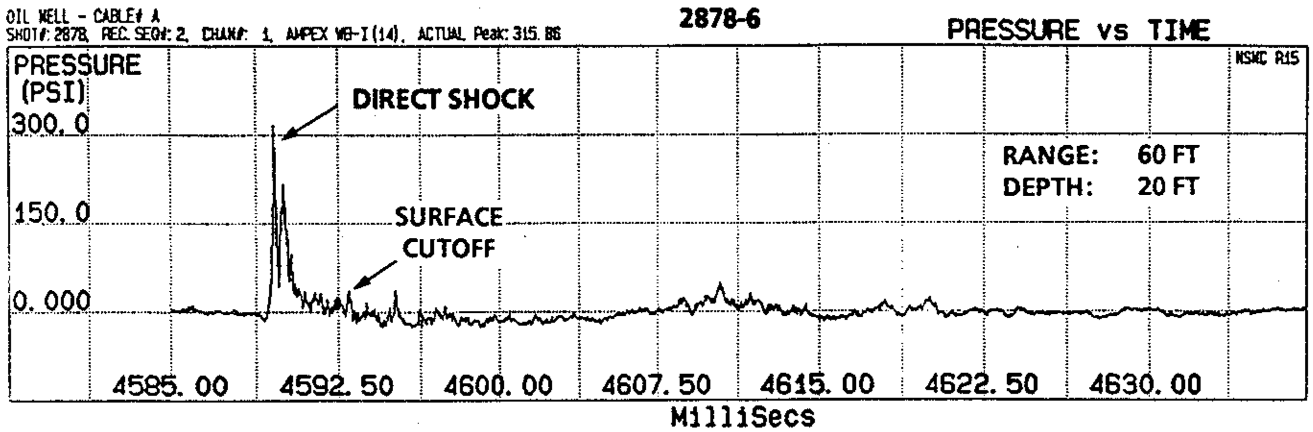
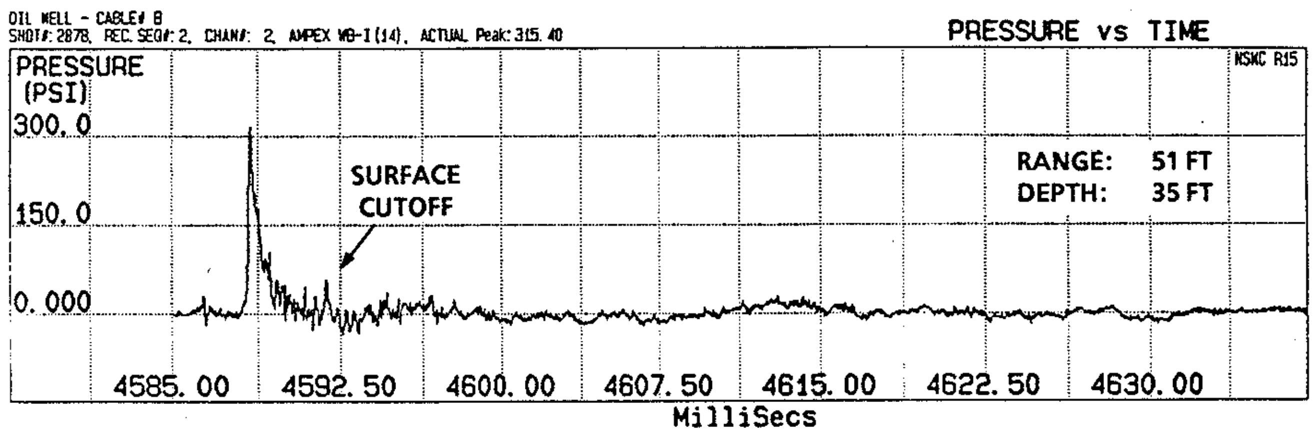


FIGURE 4-23. PRECURSOR SHOCK IMPULSE FROM MAIN JACKET PILES (16-FOOT CHARGE DEPTH)





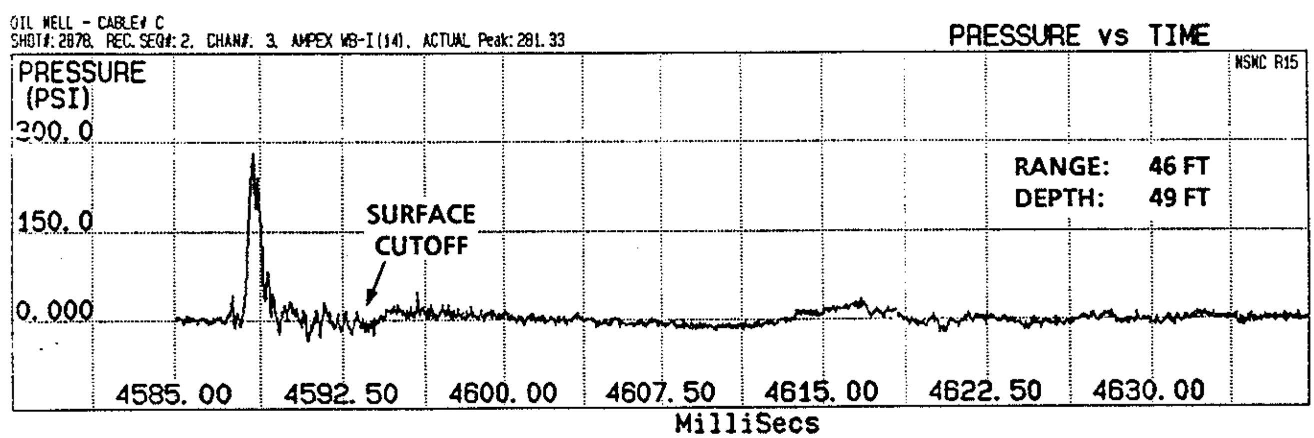


FIGURE 4-24. MAIN PILE PRESSURE RECORDS (8-FOOT CHARGE DEPTH) (FIRST GAUGE STATION)

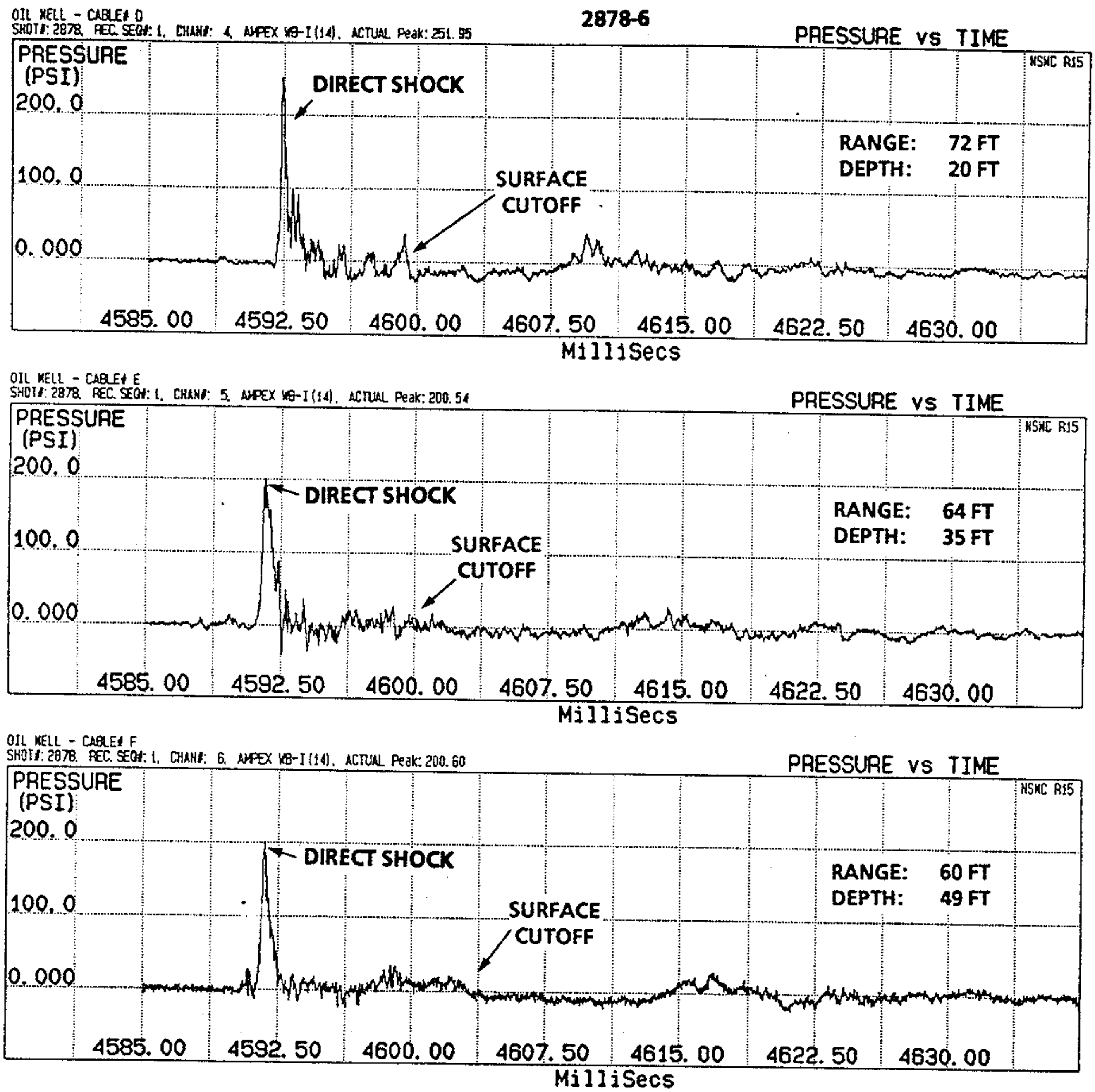


FIGURE 4-25. MAIN PILE PRESSURE RECORDS (8-FOOT CHARGE DEPTH) (SECOND GAUGE STATION)

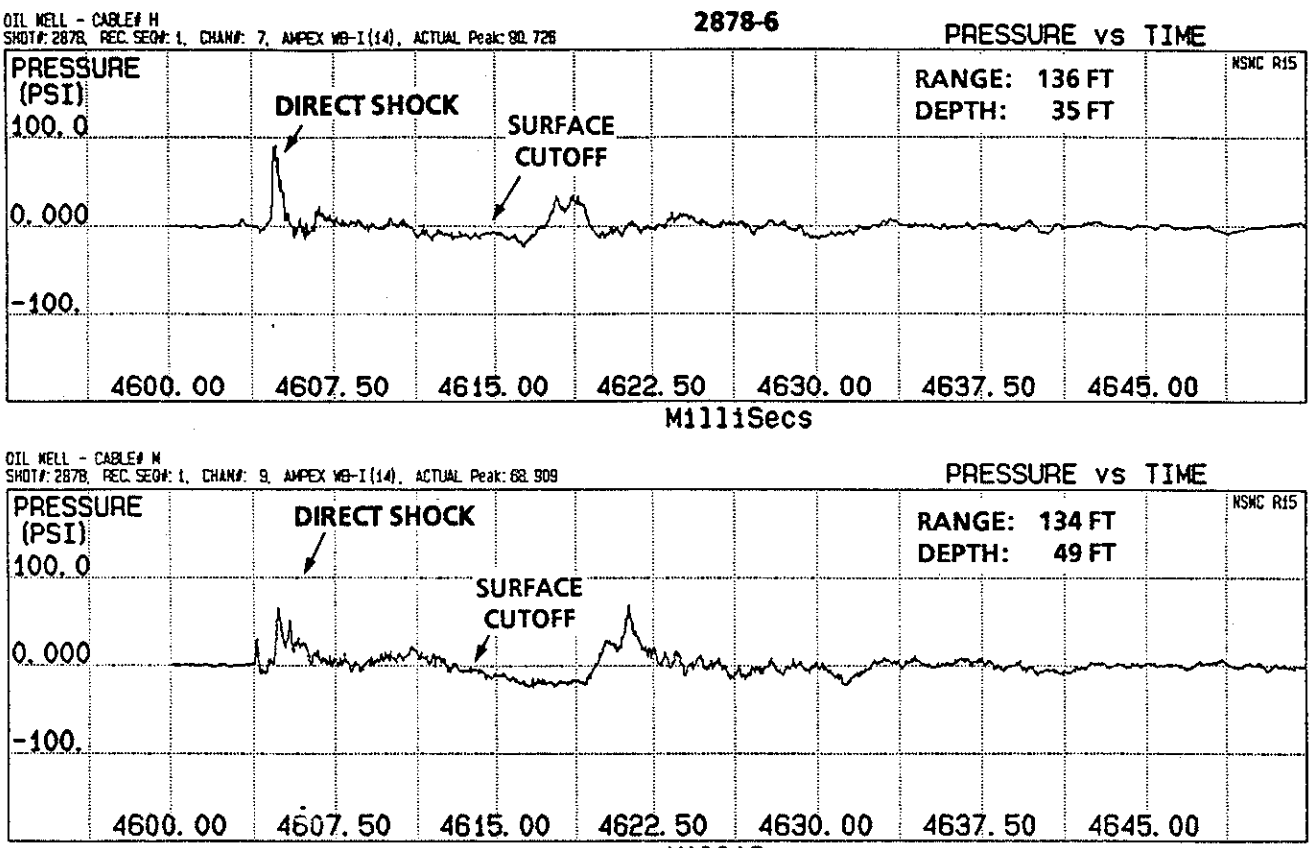


FIGURE 4-26. MAIN PILE PRESSURE RECORDS (8-FOOT CHARGE DEPTH) (THIRD GAUGE STATION)

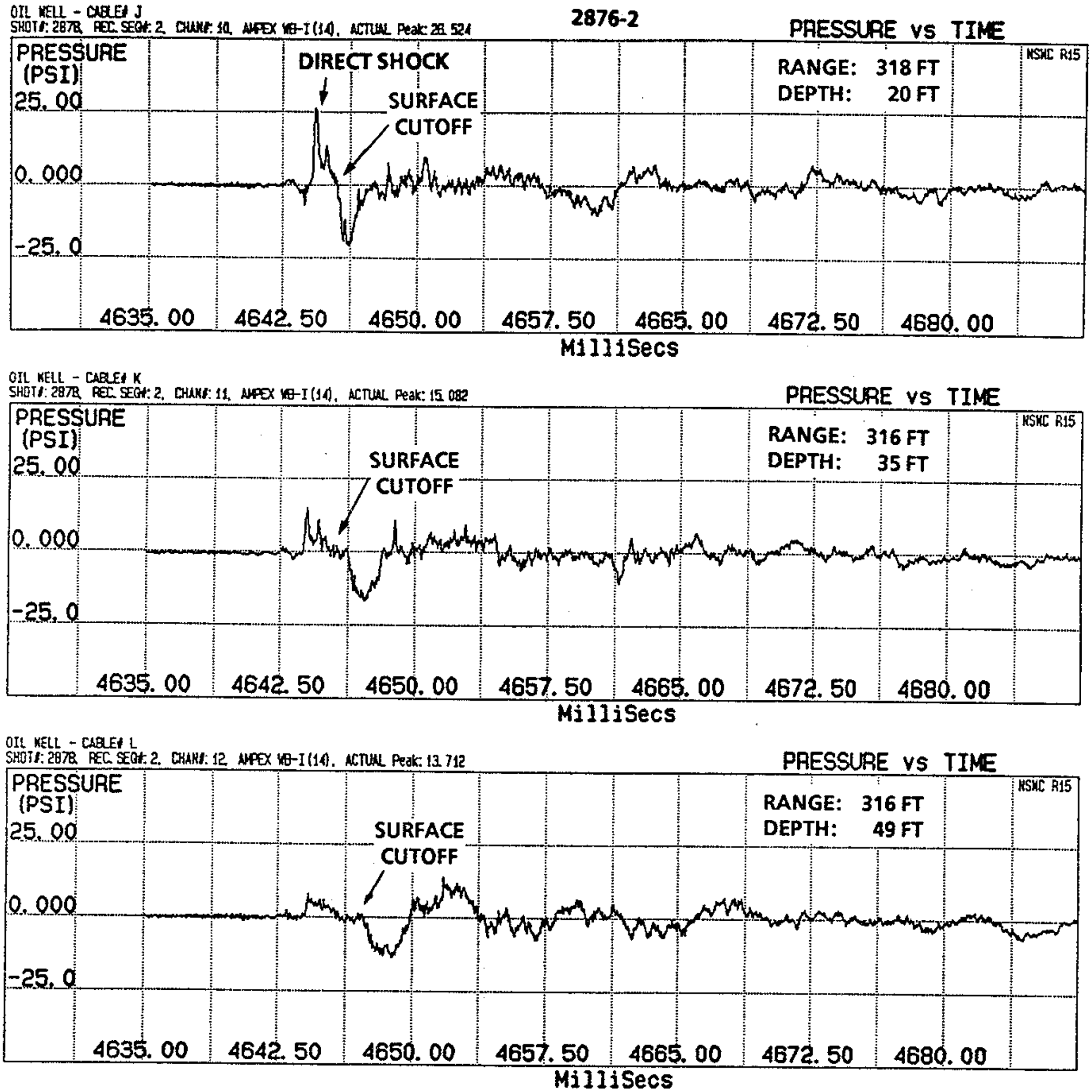


FIGURE 4-27. MAIN PILE PRESSURE RECORDS (8-FOOT CHARGE DEPTH)
(FOURTH GAUGE STATION)

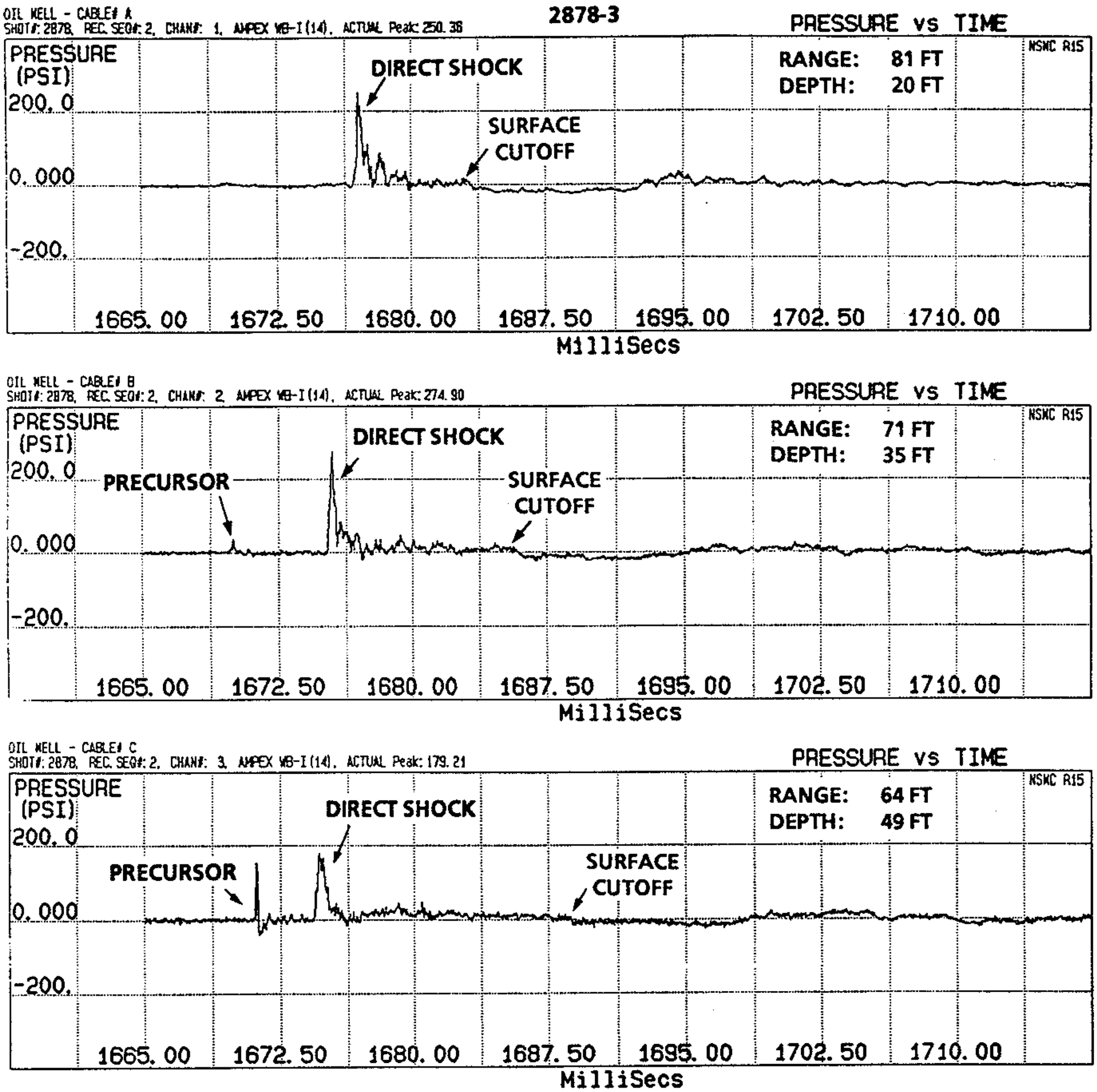


FIGURE 4-28. MAIN PILE PRESSURE RECORDS (26-FOOT CHARGE DEPTH) (FIRST GAUGE STATION)

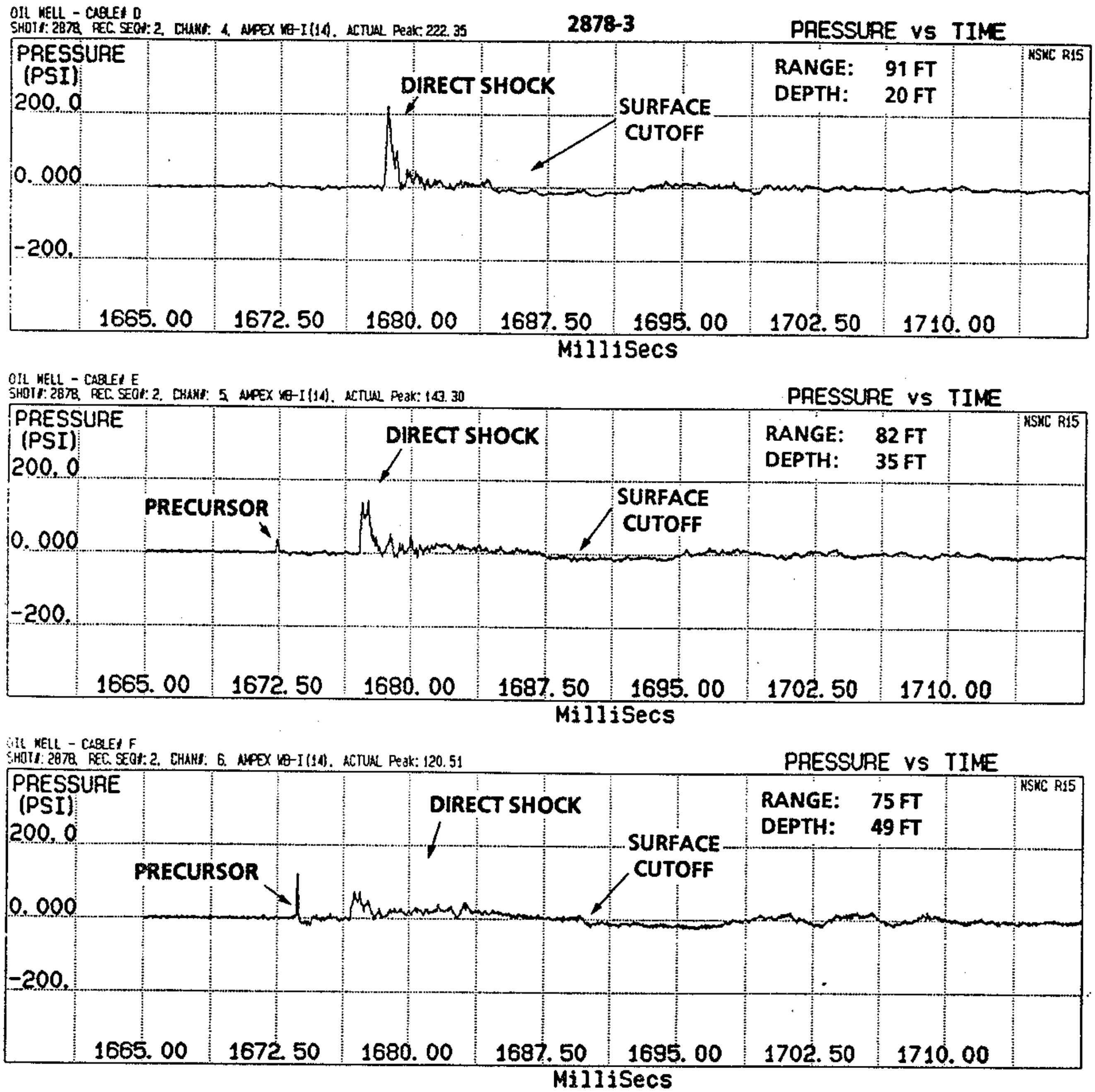
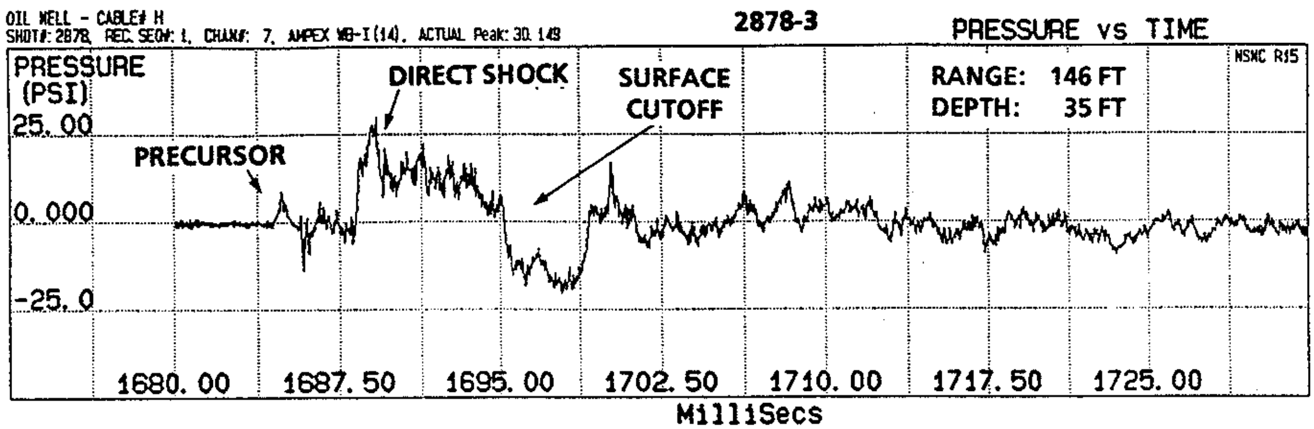


FIGURE 4-29. MAIN PILE PRESSURE RECORDS (26-FOOT CHARGE DEPTH) (SECOND GAUGE STATION)



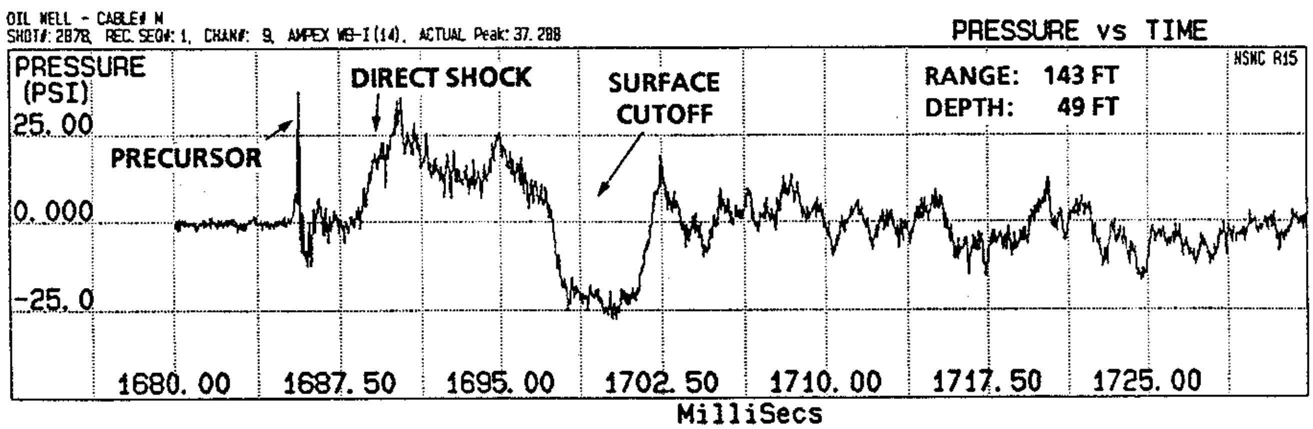


FIGURE 4-30. MAIN PILE PRESSURE RECORDS (26-FOOT CHARGE DEPTH) (THIRD GAUGE STATION)

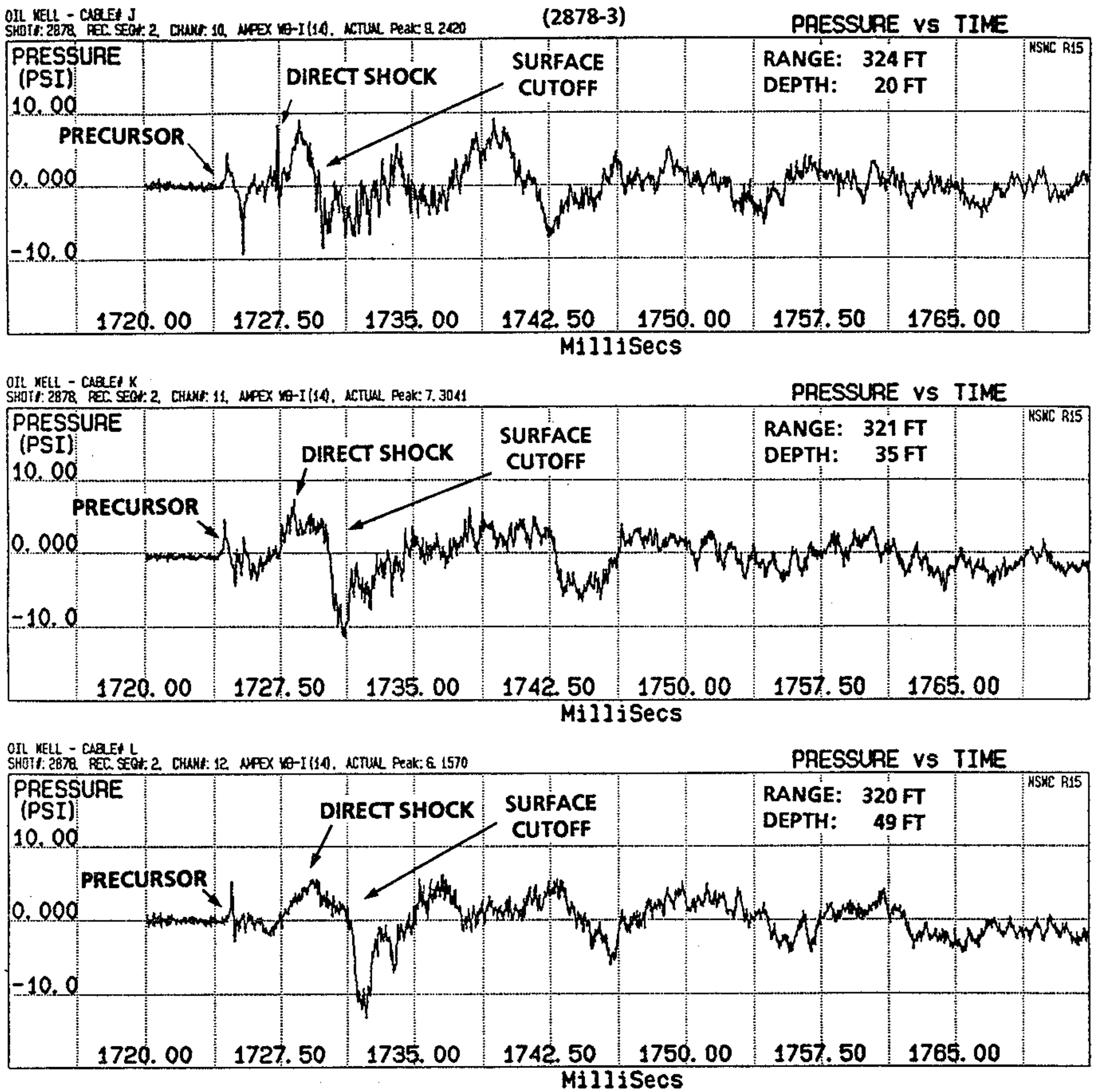


FIGURE 4-31. MAIN PILE PRESSURE RECORDS (26-FOOT CHARGE DEPTH)
(FOURTH GAUGE STATION)

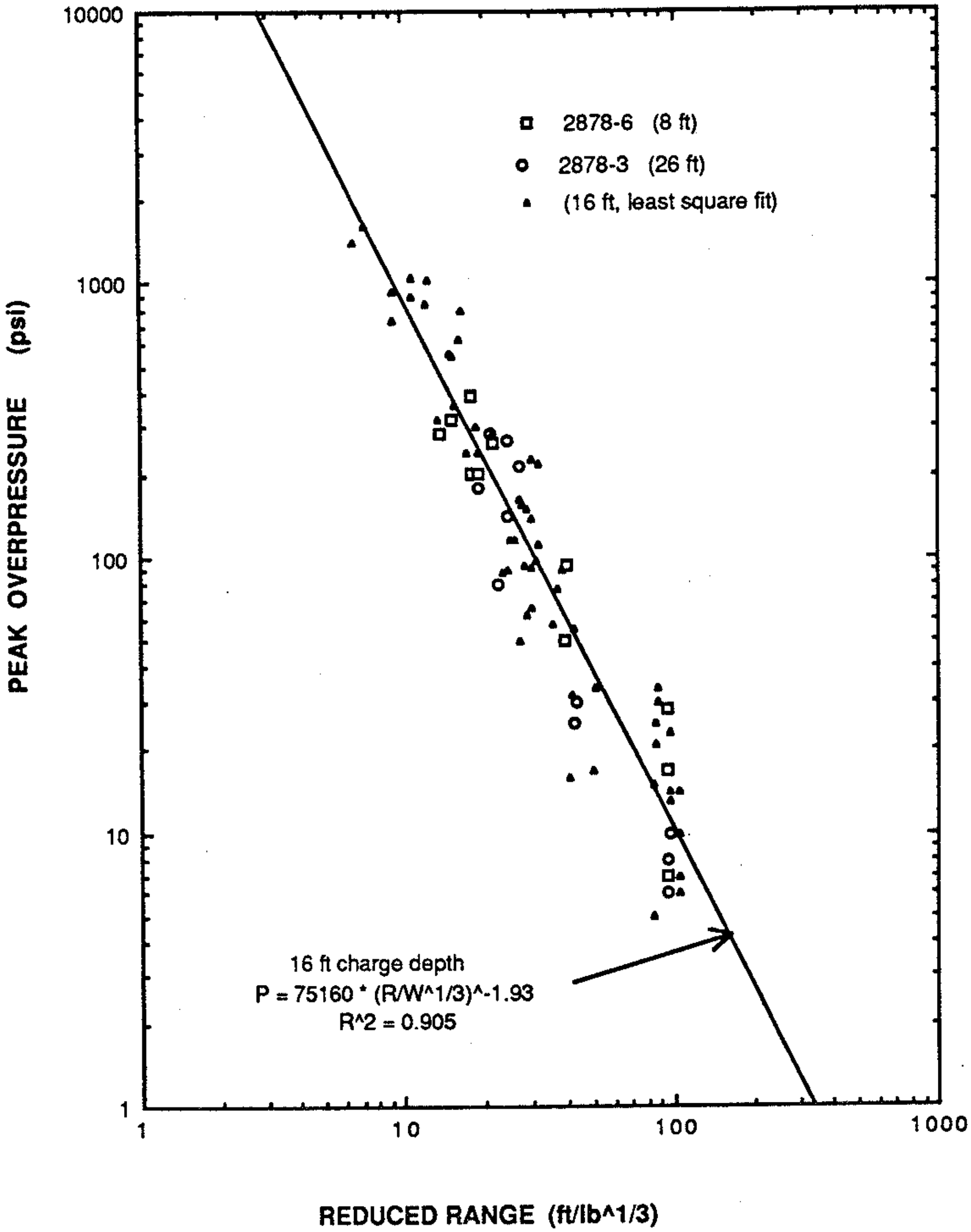


FIGURE 4-32. DIRECT SHOCK OVERPRESSURE FROM MAIN JACKET PILES FOR THREE CHARGE BURIAL DEPTHS

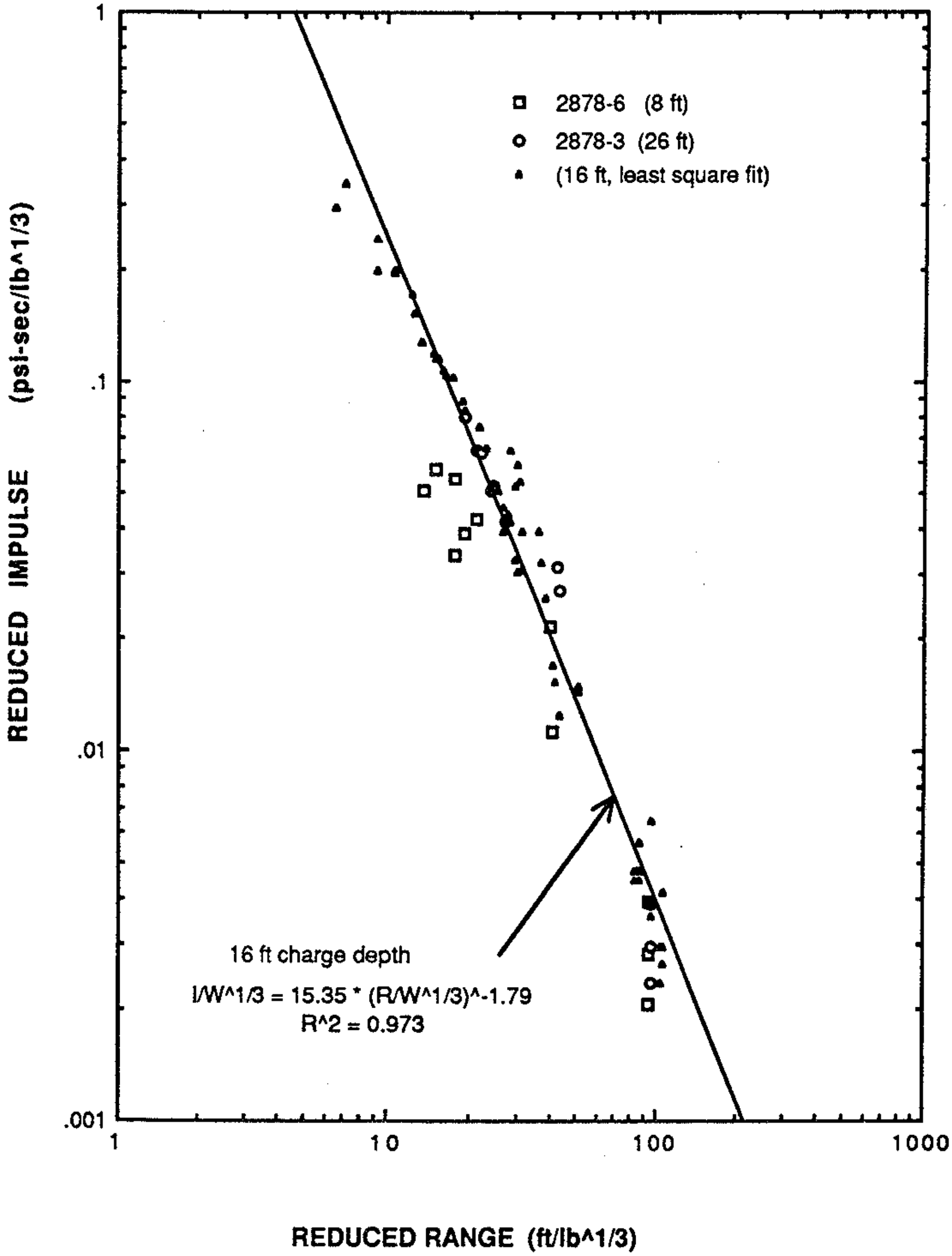


FIGURE 4-33. DIRECT SHOCK IMPULSE FROM MAIN JACKET PILES FOR THREE CHARGE BURIAL DEPTHS

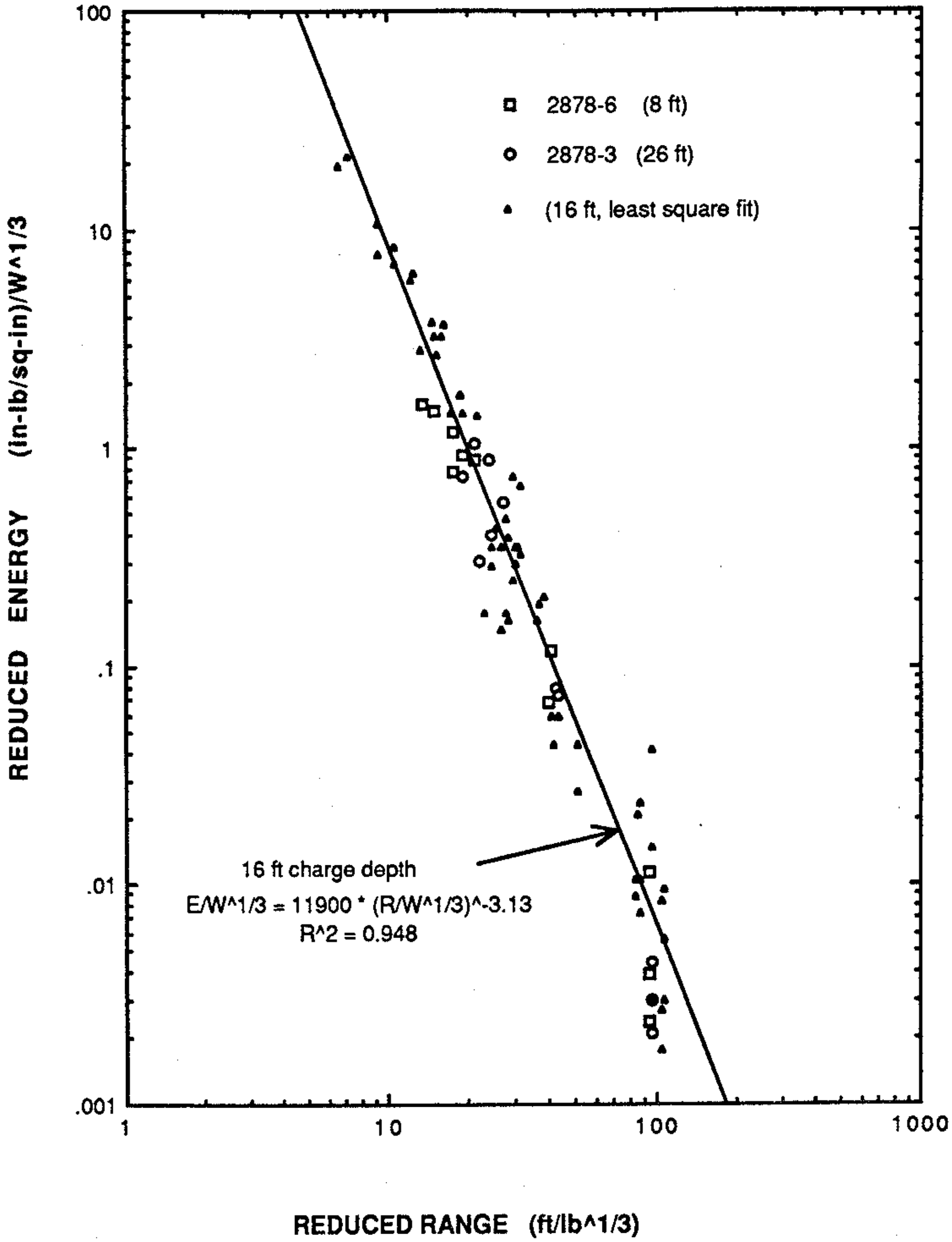


FIGURE 4-34. DIRECT SHOCK ENERGY FROM MAIN JACKET PILES FOR THREE CHARGE BURIAL DEPTHS

TABLE 4-1. BUBBLE PERIODS AND SURFACE CUTOFF TIMES
(Air Vented Well Conductors)

Shot	Gauge	Precursor Lead Time (msec)	Direct Shock Cutoff Times*		Late Pulse (msec)	Pentolite Bubble Period (msec)
			Observed (msec)	Predicted (msec)		
2875-2	A	6.7	5.1	5.7	226	260
	B	4.2	9.3	9.8	227	
	C	2.5	12.3	13.2	229	
	D	5.6	5.3	5.2	226	
(25-lb charge)	E	1.9	9.1	8.9	228	
	F	2.2	12.3	12.2	228	
	G	4.5	3.4	3.6	226	
	H	3.3	5.9	6.2	228	
	I	2.7	7.8	8.5	229	
	J	2.8	3.5	1.8	226	
	K	--	--	3.2	--	
	L	0.5	6.5	4.4	229	
2877	A	2.6	6.9	6.9	336	330
	B	1.0	11.8	11.9	340	
	C	--	15.4	16.2	342	
	D	.7	6.3	6.3	344	
(50-lb charge)	E	--	10.6	10.9	346	
	F	--	14.2	14.8	347	
	G	--	4.4	4.1	335	
	H	--	6.9	7.0	343	
	I	--	9.4	9.5	334	
	J	--	1.9	1.9	--	
	K	--	--	3.3	--	
	L	--	4.6	4.6	--	

*All times are measured from the arrival of the direct shock pulse.

TABLE 4-2. BUBBLE PERIODS AND SURFACE CUTOFF TIMES
(Well Conductors)

Shot	Gauge	Precursor Lead Time (msec)	Direct Shock Cutoff Times*		Late Pulse (msec)	Pentolite Bubble Period (msec)
			Observed (msec)	Predicted (msec)		
2876-1	A	7.8	6.6	6.7	240	260
	B	4.7	9.1	11.6	238	
	C	3.7	14.8	15.8	238	
	D	6.2	5.7	6.2	238	
(25-lb charge)	E	4.4	10.2	10.7	240	
	F	2.7	13.9	14.4	241	
	G	4.6	4.5	4.1	240	
	H	3.5	7.8	7.1	243	
	I	2.5	9.7	9.7	242	
	J	3.5	2.4	1.9	242	
	K	--	--	3.2	--	
	L	3.2	4.2	4.7	244	
2876-2	A	6.4	4.8	6.1	242	260
	B	4.2	10.0	10.4	244	
	C	3.1	13.0	14.2	247	
	D	5.7	5.4	5.6	244	
(25-lb charge)	E	3.6	9.6	9.6	247	
	F	2.4	12.5	13.1	247	
	G	4.3	4.0	3.8	242	
	H	3.5	6.2	6.6	248	
	I	2.3	8.8	9.1	249	
	J	3.8	1.6	1.9	245	
	K	--	--	3.3	--	
	L	2.8	4.6	4.6	248	

*All times are measured from the arrival of the direct shock pulse.

TABLE 4-3. SURFACE CUTOFF TIMES
(Jacket Piles)

Shot	Gauge	Precursor Lead Time (msec)	Direct Shock Cutoff Times*	
			Observed (msec)	Predicted (msec)
2878-1	A	6.8	6.4	7.9
	B	5.2	16.5	13.7
	C	2.0	18.8	19.3
	D	6.8	7.7	7.5
(16-ft burial	E	3.7	12.9	13.0
depth)	F	1.5	16.5	17.9
	G	--	--	4.5
	H	1.8	7.5	7.8
	I	.7	10.4	10.6
	J	1.5	2.0	1.9
	K	1.3	3.2	3.3
	L	.6	4.7	4.6
2880-3	A	--	4.5	6.7
	B	3.8	11.2	11.6
	C	1.5	13.5	15.7
	D	--	4.1	6.2
(16-ft burial	E	3.0	11.2	10.7
depth)	F	1.5	12.8	14.5
	G	3.0	4.5	4.4
	H	2.0	6.2	7.6
	I	1.4	4.0	10.3
	J	2.2	1.5	1.7
	K	1.5	2.2	3.0
	L	--	3.0	4.1

*All times are measured from the arrival of the direct shock pulse.

TABLE 4-3. (Cont.)

Shot	Gauge	Precursor Lead Time (msec)	Direct Shock Cutoff Times*	
			Observed (msec)	Predicted (msec)
2878-6	A	3.6	3.6	6.4
	B	2.6	3.8	10.9
	C	2.6	3.9	14.5
	D	3.0	3.4	5.7
(26-ft burial	E	1.5	3.8	9.7
depth)	F	1.5	4.9	12.9
	G	--	--	3.3
	H	2.2	2.2	5.7
	I	.4	3.8	7.8
	J	2.6	1.9	1.5
	K	2.2	3.0	2.6
	L	2.2	3.0	3.7
2878-3	A	8.5	6.5	6.5
	B	8.2	10.7	11.2
	C	4.5	13.9	15.2
	D	3.8	6.0	6.0
(8-ft burial	E	4.9	9.8	10.3
depth)	F	2.2	13.5	14.1
	G	--	--	3.9
	H	3.8	6.8	6.8
	I	3.0	8.6	9.3
	J	3.0	3.0	1.9
	K	3.0	2.6	3.4
	L	2.2	3.8	4.7

*All times are measured from the arrival of the direct shock pulse.

CHAPTER 5

SHOCK CHARACTERISTICS–WATER TERMINATION

INTRODUCTION

This chapter presents data from 8 of 10 detonations in which the charge was fired in a tubular member whose top end terminated beneath the water surface. Underwater shock pulses from six skirt pile and two well conductor detonations are discussed. The remaining two skirt pile shots are merely repetitive and provide no additional information relevant to the analysis.

Free water Pentolite explosion data is used as a comparison standard because a large body of underwater shock wave information on this explosive has been accumulated over the years. Both Composition B and Pentolite are binary mixtures of TNT with another, more sensitive, explosive. (Pentolite is PETN/TNT: 50/50, and Composition B is RDX/TNT: 60/40.) Available data indicate that the underwater shock wave/bubble output from both explosive mixtures is basically the same.[6]

On a typical underwater-terminated platform pile removal record, a single major pulse was observed. The major pulse (interpreted as the direct shock pulse because of the observed surface cutoff dip) was preceded by one and sometimes two smaller pulses. The pair (or triplet) was followed by a long-duration, low-amplitude negative excursion. Finally, a last pair of pulses (one positive and one negative) appear at a time consistent with the bubble period calculated for a free water Pentolite charge of the same weight. This bubble shock pulse has relatively small pressure amplitude but carries a specific impulse and an energy flux density comparable to those carried by the direct shock pulse. (These quantities are defined and discussed in Chapter 2.)

SKIRT PILES

Two skirt piles were located at the narrow end of each of the six leg jackets. Their upper terminations were about 20 feet below the water surface and a pair on each side of each jacket were explosively severed about 1-second apart to produce four sets of double records. No overlapping of pressure pulses was observed. As in all the other shots in the operation, no attempt was made to establish or to maintain any particular separation between the charge and the steel wall of the tubular member.

Pressure-time Records

Sample pressure-time records for one pair of the skirt pile shots are shown in Figures 5-1 to 5-5. Identifiable features discussed in Chapter 3 are indicated on each figure.

These figures show the records obtained when two skirt piles (one at each end of one of the platforms) were explosively severed about 1 second apart. The top trace in each figure shows the entire record from before the first detonation to well after the second. The middle trace on each of the figures is an enlargement of the direct shock portion of the first of the two detonations. The second detonation, which occurred farther away from the gauges, produced a similar but lower amplitude pulse. A definite, but lone, precursor is observed on these shots. (Recall that the tops of these piles are only 20 feet below the water surface.) The bottom third of each figure shows the late pulse which has been associated with the collapse of the explosion gas bubble.

Figure 5-5 shows the pressure-time records obtained at all three gauge depths at the second station. A precursor appears closer to the direct shock pulse as gauge depth increases. The precursor amplitude decreases at the farther out stations and is sometimes hard to identify.

Similitude Plots

Shock overpressure and reduced impulse and energy for the direct shock pulse are displayed as functions of reduced range in Figures 5-6 to 5-8. All have either lower moduli or decay with range at much higher rates than the corresponding free water Pentolite values for each quantity. At reduced ranges greater than 100 ft/lb$^{1/3}$ all of the quantities observed near the skirt pile detonations are less than 10 percent of the corresponding archival free water Pentolite values.

Direct Shock. Figures 5-6 to 5-8 represent the pressure and reduced impulse and energy carried by the direct shock. Each quantity is plotted as a function of reduced range. As a reference, each figure includes a line representing the archival free water Pentolite values for the same quantities.

Overpressure and energy values all fall below the Pentolite line and become insignificant (relative to Pentolite results) at reduced ranges exceeding 100 ft/lb$^{1/3}$. At close-in ranges, however, impulse (Figure 5-7) approaches an asymptote somewhat above the free water Pentolite line. At greater ranges, the shock impulse, like pressure and energy, falls well below the Pentolite line.

This seeming enhancement of impulse is in part due to a difference in integration technique: the Pentolite impulse values were calculated by summing the area under the pressure-time curve for five time constants of the decay of an exponentially decaying pressure-time curve. The calculation for the current shots was extended to the time at which surface cutoff occurred. This is a somewhat greater integration time than used in free water Pentolite experiments.

On these three plots, a distinction is made between shots with different charge burial depths. On each plot there are three sets of data for each of two burial depths: 16 and 26 feet below the sea bottom. Each group is represented by a different plot symbol. Scatter is great enough that no significant difference can be noted between the two groups of points.

Bubble Shock. Figures 5-9 to 5-11 are similitude plots of reduced data for the "late" pulse. This pulse is thought to originate in the explosion bubble collapse.

Overpressure and energy are lower than the corresponding direct shock free water Pentolite values. Bubble energy and overpressure are also lower than the overpressure and energy determined for the direct shock on these shots.

Impulse, shown in Figure 5-10, approaches the Pentolite line as closely as the direct shock impulse does. There is more scatter evident in the bubble impulse data. This is indicated by comparing the correlation coefficient for the bubble fit (0.78) with the correlation coefficient for the direct shock data fit (0.92, as shown in Figure 5-7).

Discussion

Precursor Pulse. The precursor, when present, has about the same amplitude as the direct shock pulse. On some records, the amplitude of the precursor is quite small relative to the direct shock pulse on the same record. The amplitude of the precursor on these shots is comparable to that of the direct shock on the more distant gauges.

The precursor duration is much less than that of the direct shock immediately following it. In all observed cases, the impulse and energy carried by the precursor pulse is considerably less than that carried by the main shock and the bubble pulses.

The source of the precursor has not been identified–except that it is probably nearer the water surface than the bottom since it appears earlier on the top-most gauge in each vertical string than on the lower gauges in the same string. This is illustrated in Figure 5-5.

Direct Shock Pulses. Direct shock peak pressure, impulse, and energy approach values to be expected from Pentolite at short ranges from the explosions. These parameters are plotted versus reduced (slant) range ($R/W^{1/3}$) in Figures 5-6 to 5-8. Each graph includes the appropriate archival free water Pentolite data for comparison. Slopes of the lines fitted to the well conductor data are steeper than for Pentolite, so that at longer ranges all three parameters rapidly fall away to much less than 10 percent of free water Pentolite values at 300- to 500-foot ranges.

Impulse and energy observed on shallow gauges may be less than the values calculated for free water Pentolite because the direct shock pulses are terminated by the rarefaction reflected from the water surface. This shortening effect becomes less dominant at greater gauge depths. Despite this tendency to shorter pulse length, the impulse data from the well conductor shots is higher at close-in ranges than the Pentolite values for the same ranges and charge weights. The reason for this is not obvious.

Surface Cutoff. The direct shock is reflected from the free water surface as a rarefaction. When the rarefaction reaches a gauge, it abruptly terminates the "smooth" decay of the direct shock pulse toward the baseline. Times observed on the platform removal shots for these cutoffs agree well with values predicted from the charge/gauge geometry–and facilitate the identification of the primary shock pulse amongst the wild gyrations of the pressure recordings. A sampling of surface measured cutoff times is presented in Table 5-1 together with predictions based on shock speed and gauge and charge depths. The calculation is described in Reference 7.

Bubble Periods. When the gaseous explosion product bubble collapses on itself following its initial overexpansion, a pulse is emitted into the surrounding water. The times after direct shock arrival at a particular gauge at which the "late" pulse occurs are tabulated for two shots in Table 5-1. These times agree closely with bubble periods calculated for archival Pentolite of the same charge weights. Pentolite bubble periods are also listed in Table 5-1.

Bubble Pulses. Peak pressure, impulse, and energy from the bubble pulses, though less than the values associated with the direct shock, are still significant. These parameters are plotted versus reduced slant range ($R/W^{1/3}$) in Figures 5-9 to 5-11, together with Pentolite shock data. Peak pressure and energy values fall noticeably below the Pentolite values while impulse matches the Pentolite shock values at close-in ranges. It should be noted that the impulse produced by the bubble pulse is sensibly the same as the direct shock impulse, while the bubble energy and overpressure are definitely less than those produced by the direct shock. All three parameters fall off rapidly with range, becoming insignificant beyond reduced range of 100 ft/lb$^{1/3}$.

Cavitation. Pulses of relatively small amplitude are seen shortly after the direct shock pulse on most records. These probably occur when the surface cavitation layer collapses on itself. This is a water hammer effect, similar to the thump sometimes heard when a water faucet is closed suddenly. Amplitude and duration of this pulse are small enough that the pulses were not analyzed.

Negative Pressures. Pressure sensed and reported by the gauges became less than ambient at two times on the signatures: immediately following the surface cutoff of the direct shock pulse and immediately following the positive bubble pulse. In both cases, the amplitude was usually about 25 to 30 psi, occasionally reaching 40 to 50 psi. Natural water tends to break up into cavitation bubbles when subjected to tensions greater than 30 to 50 psi. Therefore, it is difficult to state unequivocally that the negative pressures reported are really pressures in the water. The values observed are more likely to be the values of pressures in a bubbly cavitated region at the gauge surface. However, these pressures are just those that would be experienced by any solid obstacle in the pressure field around an underwater explosion near enough to the surface to experience surface cutoff.

WELL CONDUCTORS

During the operating life of the production platform, two of the conductors had been cut off at about 45 feet below the water surface. For the removal operation, both were scoured out sufficiently to allow 25-pound octagonal charges to be lowered inside them to 18 feet below the mud line. Each was fired individually–not in tandem with a delay.

Pressure-time Records

Sample pressure-time records from one of the submerged well conductor shots are shown in Figures 5-12 to 5-16. Identifiable features discussed in Chapter 3 are indicated.

Figures 5-12 to 5-15 show the records obtained at the top gauge at each station when a single conductor with its top 45 feet below the water surface was fired alone. The top trace in each figure shows the entire record. The middle trace on each of the figures is an enlargement of the direct shock portion of the detonation signal. Two precursors are observed on these records. (Recall that the tops of these piles are only 45 feet below the water surface.) The bottom third of each figure shows the late pulse which has been associated with the collapse of the explosion gas bubble.

Figure 5-16 shows the variation of precursor lead time with gauge depth. The second precursor increases in amplitude with respect to the first precursor as gauge depth increases. It is conceivable that the two precursors meld into one when shot conditions change. For example, there is only one precursor on the skirt pile detonation records–the tops of these piles were closer to the water surface than the well conductors being considered here.

Similitude Plots

Overpressure and reduced impulse and energy for both the direct shock and the bubble shock are plotted in Figures 5-17 to 5-19. Overpressure and energy from the bubble is noticeably less than the same quantities from the direct shock. Both fall below the free water Pentolite values. The goodness of fit indicated by the correlation coefficient of the least square fit for the direct shock ($R^2 \sim 0.6$) reflects the large amount of scatter in this data. By comparison, the fit to the bubble data is quite good ($R^2 \sim 0.9$).

As for several other cases discussed in this report, the impulse produced for both the bubble and the shock pulses is about the same. Impulse values are also close to the free water Pentolite line at close-in ranges. Again, the direct shock impulse data exhibits considerably more scatter than does the bubble data–as indicated by the correlation coefficient ($R^2 \sim 0.6$).

Discussion

Precursors. Peak pressure and reduced impulse and energy for both of the precursors are plotted as functions of reduced range in Figures 5-20 to 5-22. There is no evident difference between the values for the two pulses. Both start at about 60 percent of the free water Pentolite values at close-in ranges and fall to a small fraction of the Pentolite values at ranges exceeding about 75 ft/lb$^{1/3}$.

Direct Shock and Bubble Pulses. Direct shock peak pressure and reduced energy for these submerged well conductor shots are both larger than the same quantities produced by the bubble pulses. Both are less than the free water Pentolite values, as shown in Figures 5-17 and 5-19. On the other hand, impulse for both of these portions of the signal is about the same as free water Pentolite at close-in ranges.

All three parameters decay with range to the extent that each is negligible at reduced ranges exceeding 100 ft/lb$^{1/3}$.

Surface Cutoff. The tension wave reflected from the water surface produces a negative pulse superposed on the decay portion of the direct shock pulse. Times of occurrence of the cutoff pulses agree closely with geometrical predictions. Observed and predicted values are listed in Table 5-2.

Bubble Periods. The time interval between arrival of the direct shock and the arrival of the "late" pulse at each gauge agree well with the bubble period predicted from archival free water Pentolite data for charges weighing 25 pounds.

Cavitation. Pulses of relatively small amplitude are seen shortly after cutoff of the direct shock pulse on most records. These probably occur when the surface cavitation layer collapses on itself. This is a water hammer effect, similar to the thump sometimes heard when a water faucet is closed suddenly. Amplitude and duration of this pulse are small enough that the pulses were not analyzed.

Negative Pressures. Pressure sensed and reported by the gauges became less than ambient at two times on the signatures: immediately following the surface cutoff of the direct shock pulse and immediately following the positive bubble pulse. In both cases, the amplitude was usually about 25 to 30 psi, occasionally reaching 40 to 50 psi. Natural water tends to break up into cavitation bubbles when subjected to tensions greater than 30 to 50 psi. It is therefore difficult to state unequivocally that the negative pressures reported are really pressures in the water. The values observed are more likely to be the values of pressures in a bubbly cavitated region at the gauge surface. However, these pressures are just those that would be experienced by any solid obstacle in the pressure field around an underwater explosion near enough to the surface to experience surface cutoff.

DISCUSSION

For these cases in which the charge was fired in a tubular member whose top end terminated below the water surface, the sequence of pulse arrival times seems strange. The first one (or two) of the group of two or three arrive at the top gauges on each down line earlier than at the lower gauges on the same line. The last pulse of the group arrives at the lowest gauge on each line before the upper gauges on the same line.

Since all the charges were mounted below the lowest gauge, the direct shock emitted by the explosion appears first at the lowest gauges on each string (because of the shorter travel distance), reaching each higher gauge in upward succession. Conversely, a pulse originating near the water surface should appear first at the top-most gauge in each string, then at each lower gauge in downward succession.

Following the above argument, the first two pulses appear to originate at or near the water surface. The first pulse of the group of three exhibits a shape reminiscent of surface cutoff (except that the cutoff time is much too short).

The second pulse of the group of three exhibits some of the characteristics of the smaller pulse that precedes the direct shock wave observed on the air-terminated severance shots discussed in Chapter 4. Its amplitude varies with depth and it arrives earlier at the shallower gauges (nearest the water surface). Its apparent source is not obvious.

In those cases where there are only two pulses in the group, it is difficult to determine whether the precursor corresponds to the first or the second of the group of three.

Amplitudes of the (one or two) precursors at far ranges are so small that the signals are buried in noise and hard to identify.

The last of the three early pulses to arrive at each gauge station is identified as the direct shock emitted from the charge inside the tubular below the mud line. It arrives later at the shallower gauges. At most of the gauges, the shock pulse is cut off at times that agree with the geometrical calculation of surface cutoff times described in the preceding chapter.

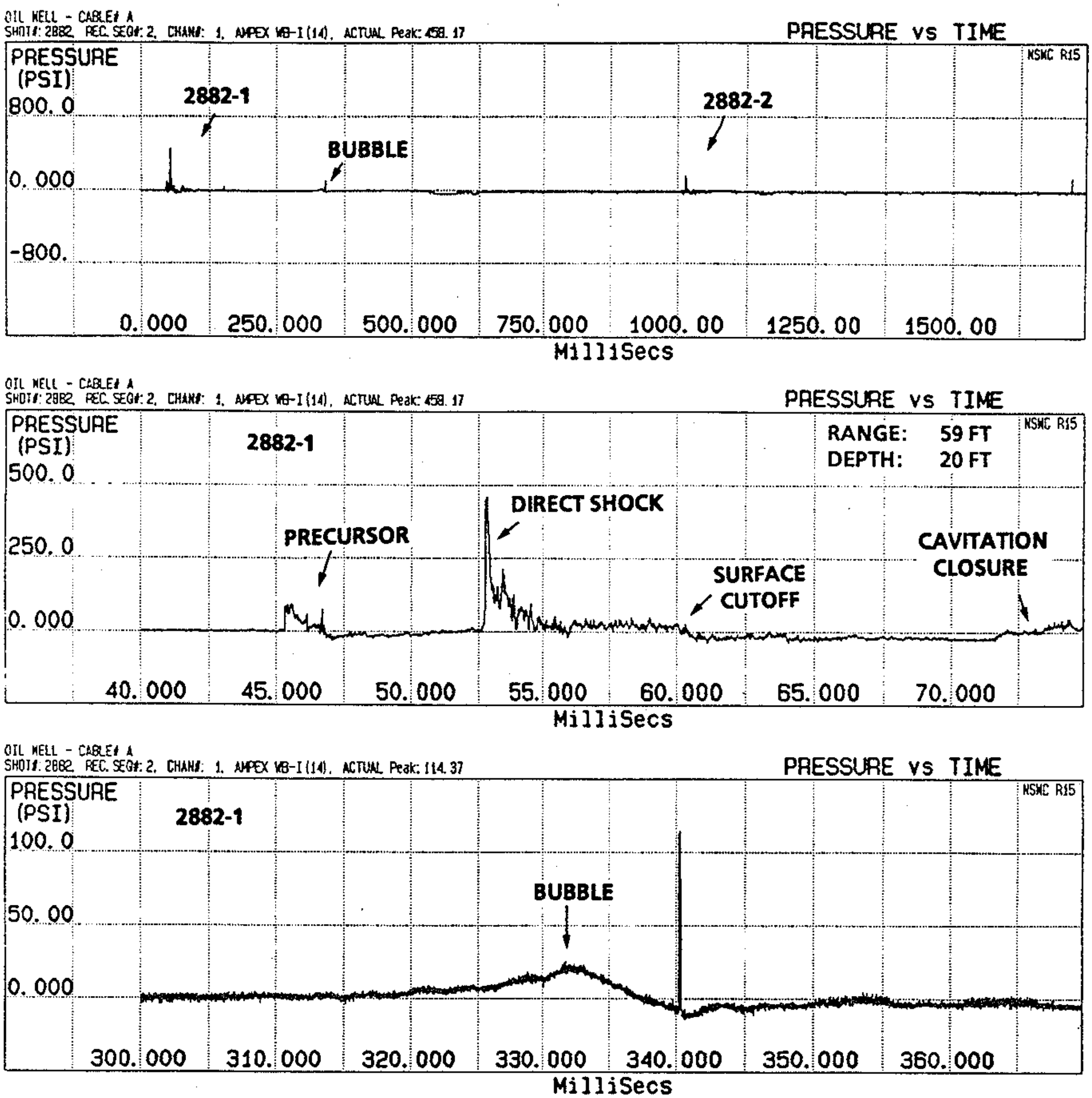


FIGURE 5-1. SKIRT PILE PRESSURE RECORDS
(TOP GAUGE AT FIRST STATION)

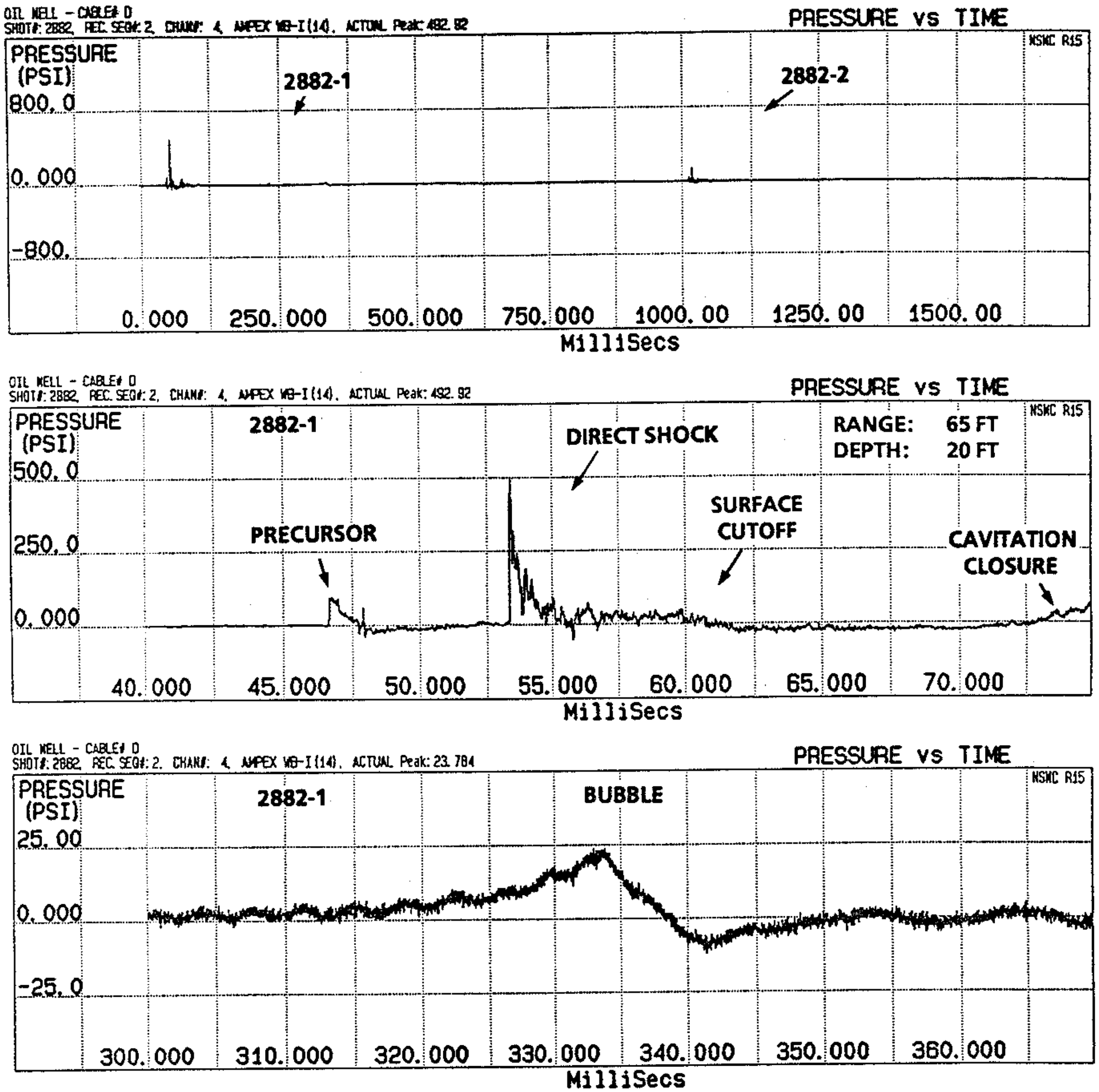


FIGURE 5-2. SKIRT PILE PRESSURE RECORDS
(TOP GAUGE AT SECOND STATION)

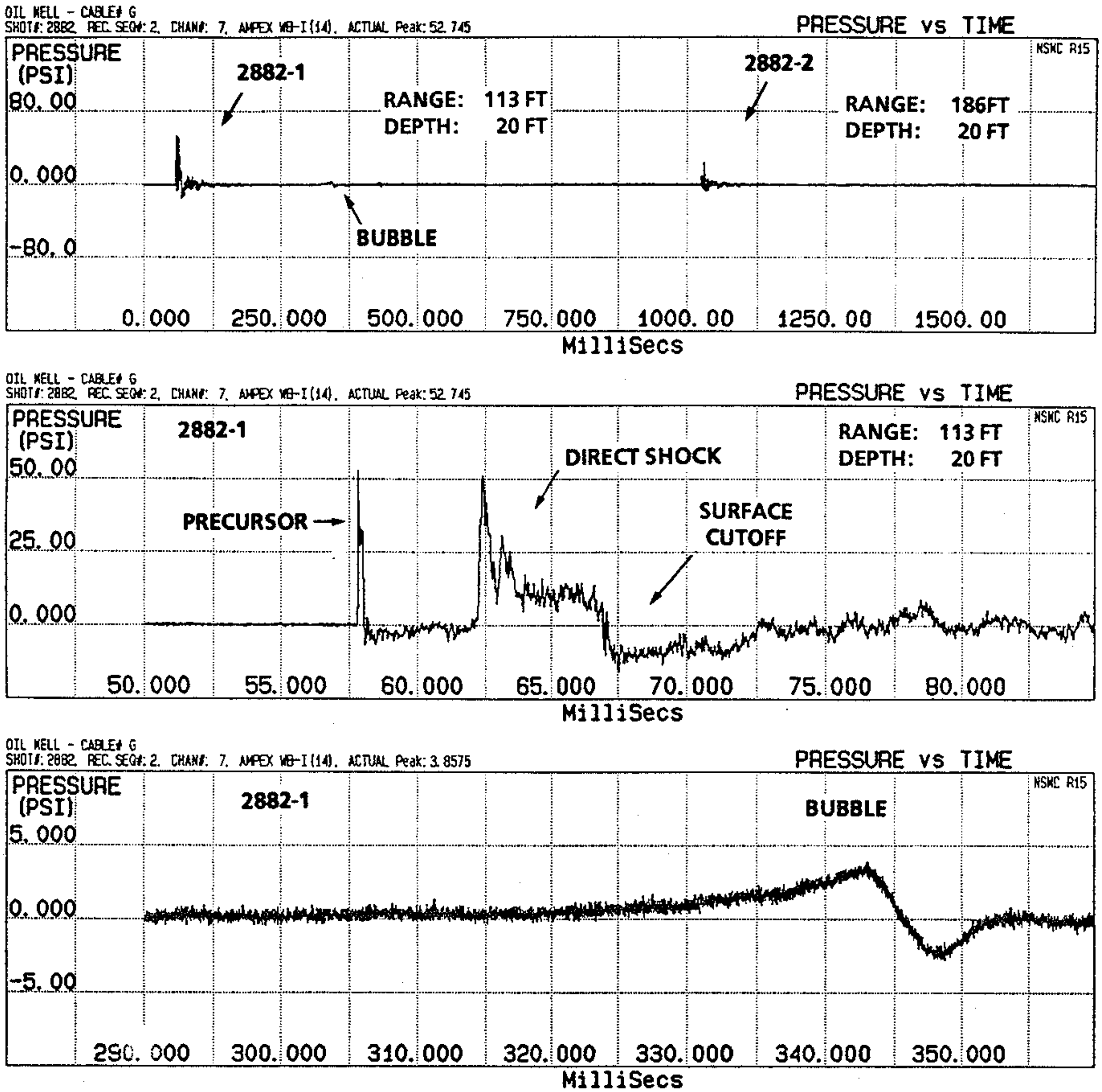


FIGURE 5-3. SKIRT PILE PRESSURE RECORDS
(TOP GAUGE AT THIRD STATION)

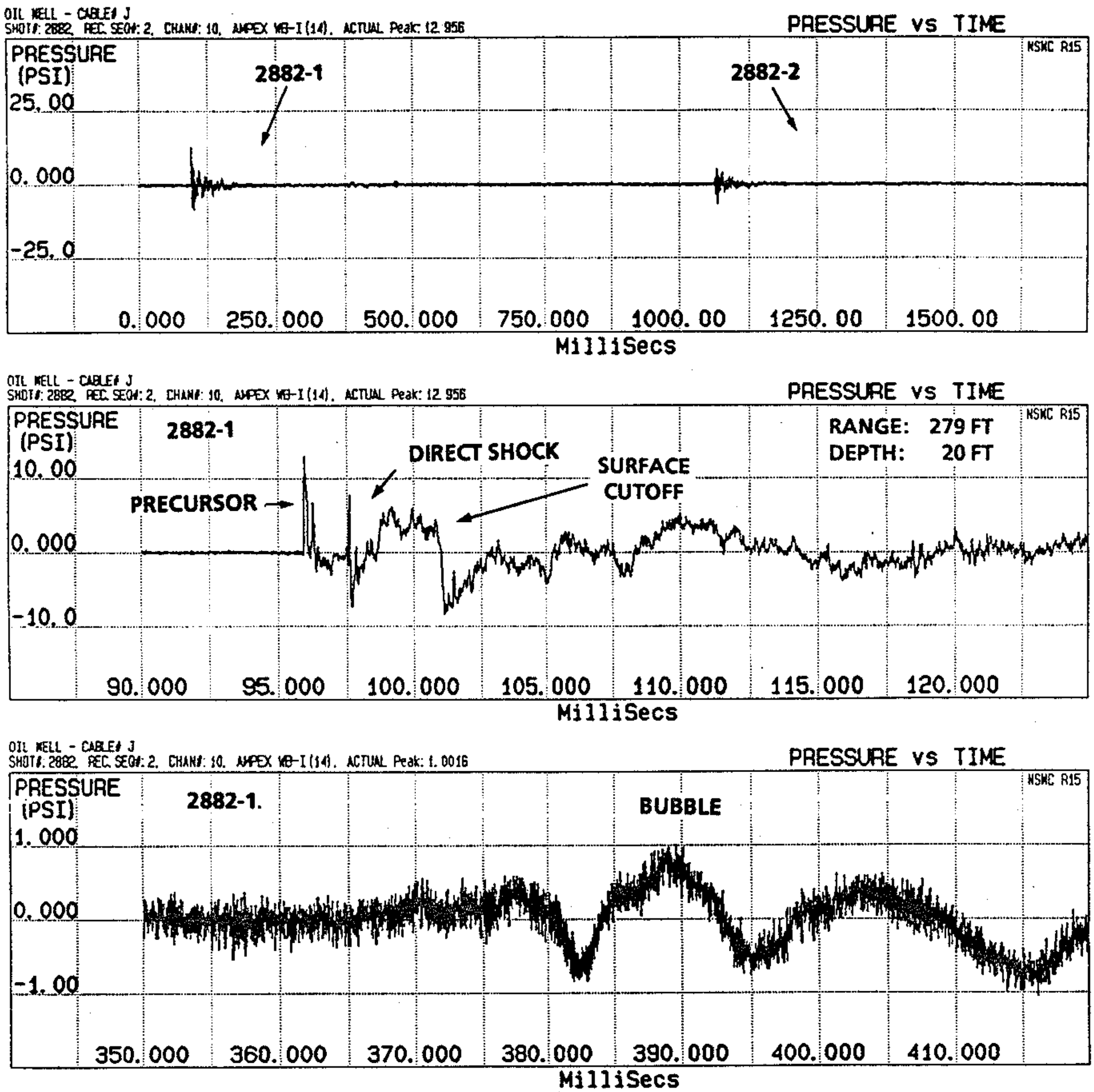


FIGURE 5-4. SKIRT PILE PRESSURE RECORDS
(TOP GAUGE AT FOURTH STATION)

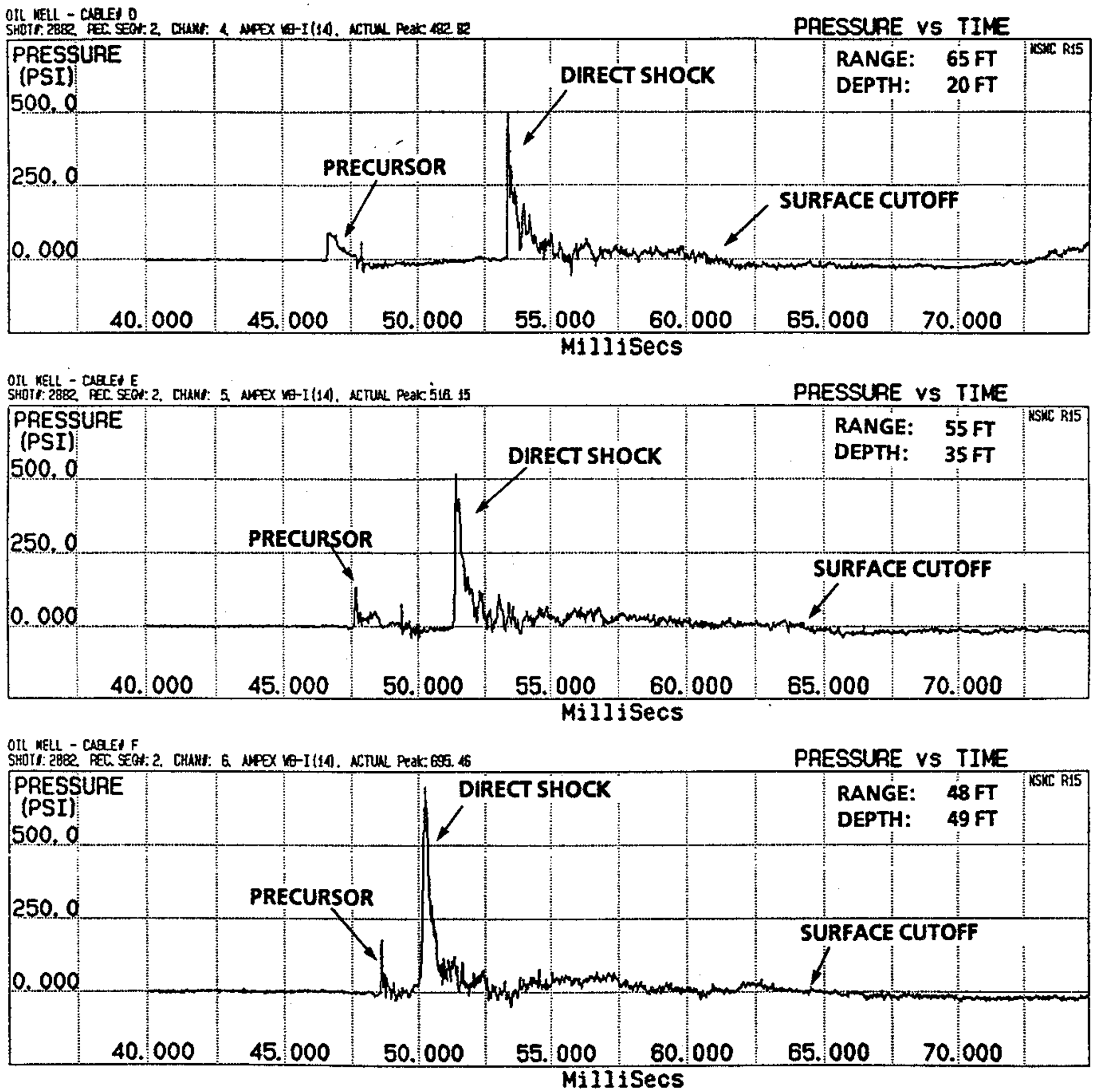


FIGURE 5-5. SKIRT PILE PRESSURE RECORDS
(PRECURSOR AT SECOND STATION)

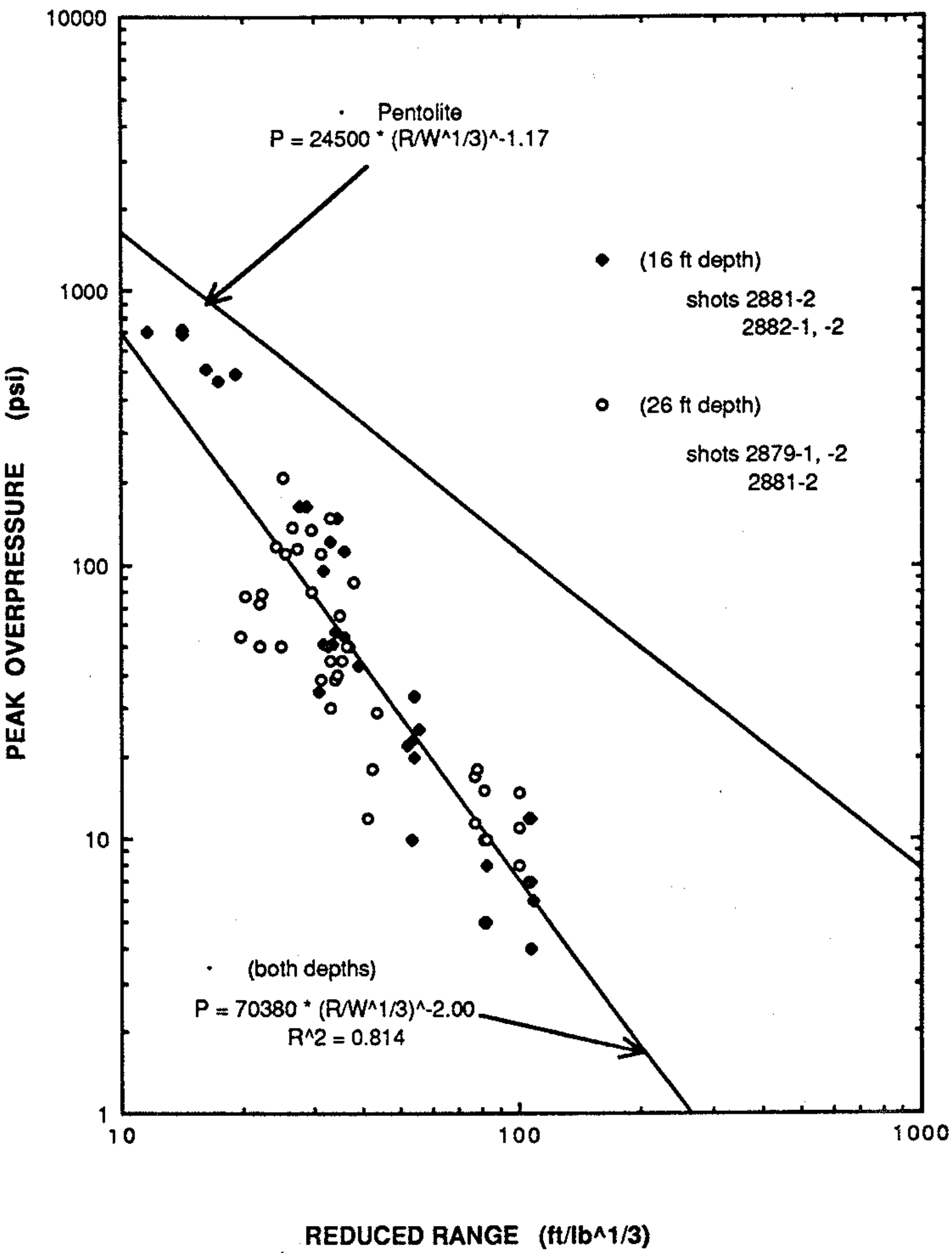


FIGURE 5-6. DIRECT SHOCK OVERPRESSURE FROM SKIRT PILES
(16- AND 26-FOOT CHARGE DEPTHS)

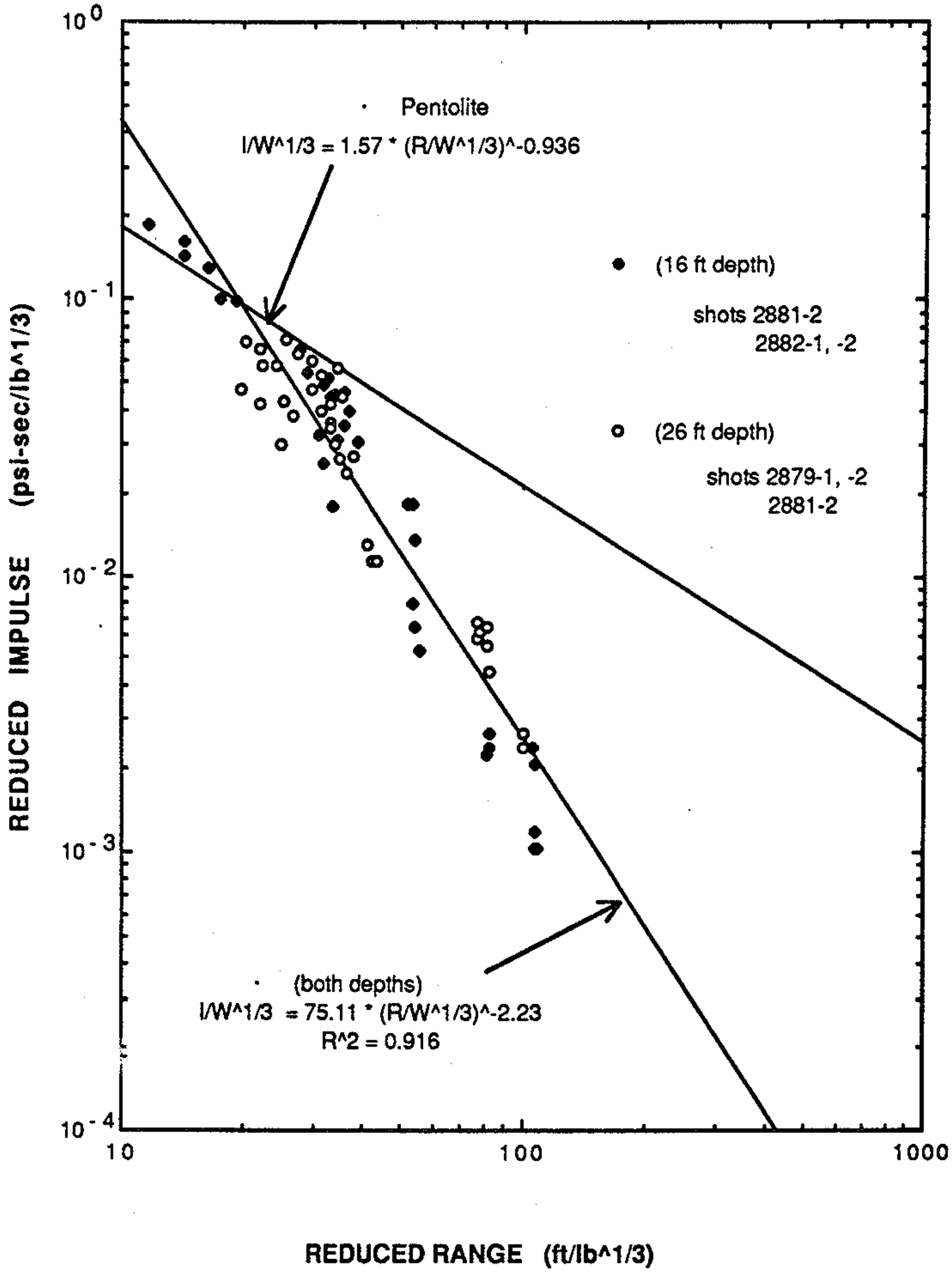


FIGURE 5-7. DIRECT SHOCK IMPULSE FROM SKIRT PILES (16- AND 26-FOOT CHARGE DEPTHS)

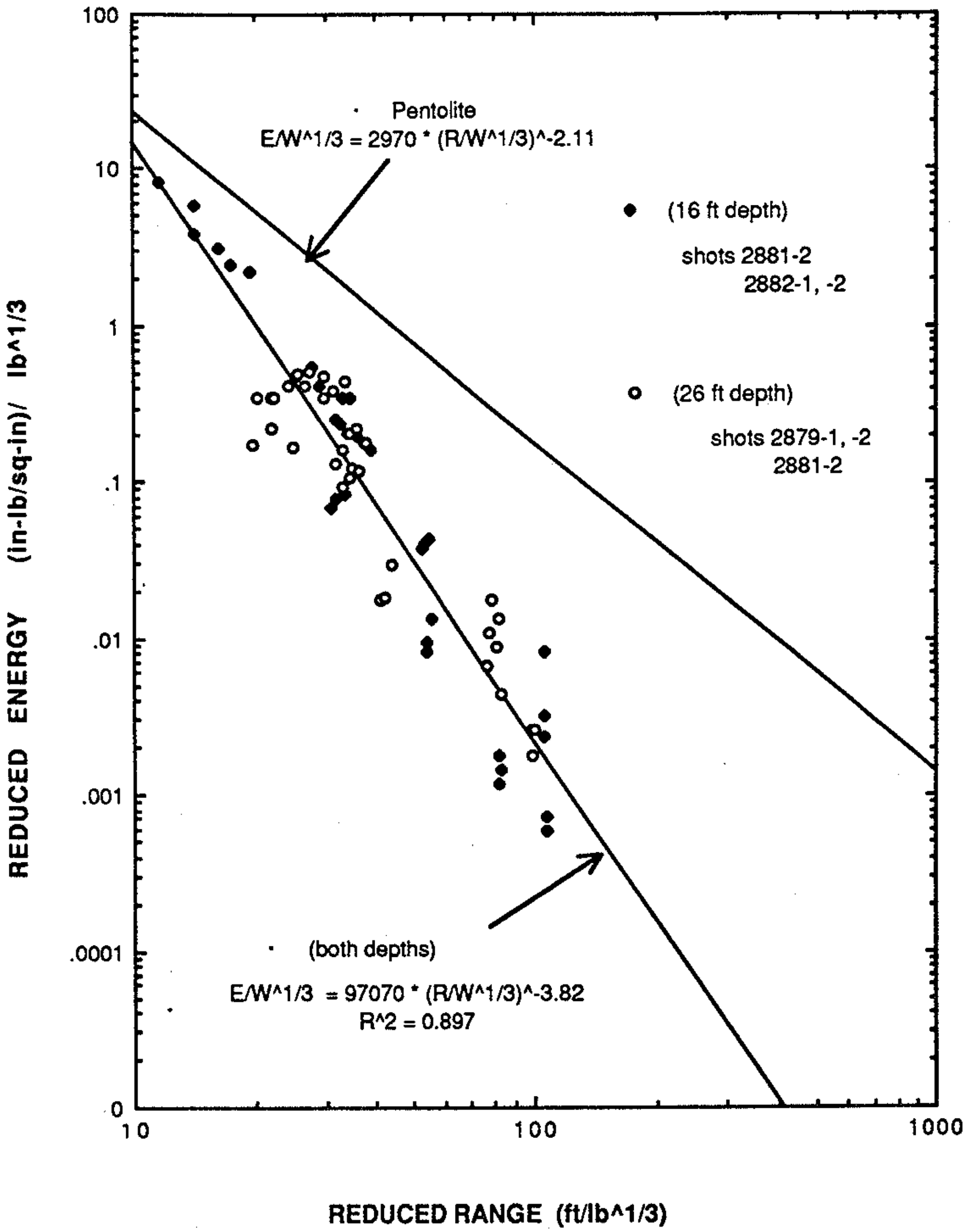


FIGURE 5-8. DIRECT SHOCK ENERGY FROM SKIRT PILES
(16- AND 26-FOOT CHARGE DEPTHS)

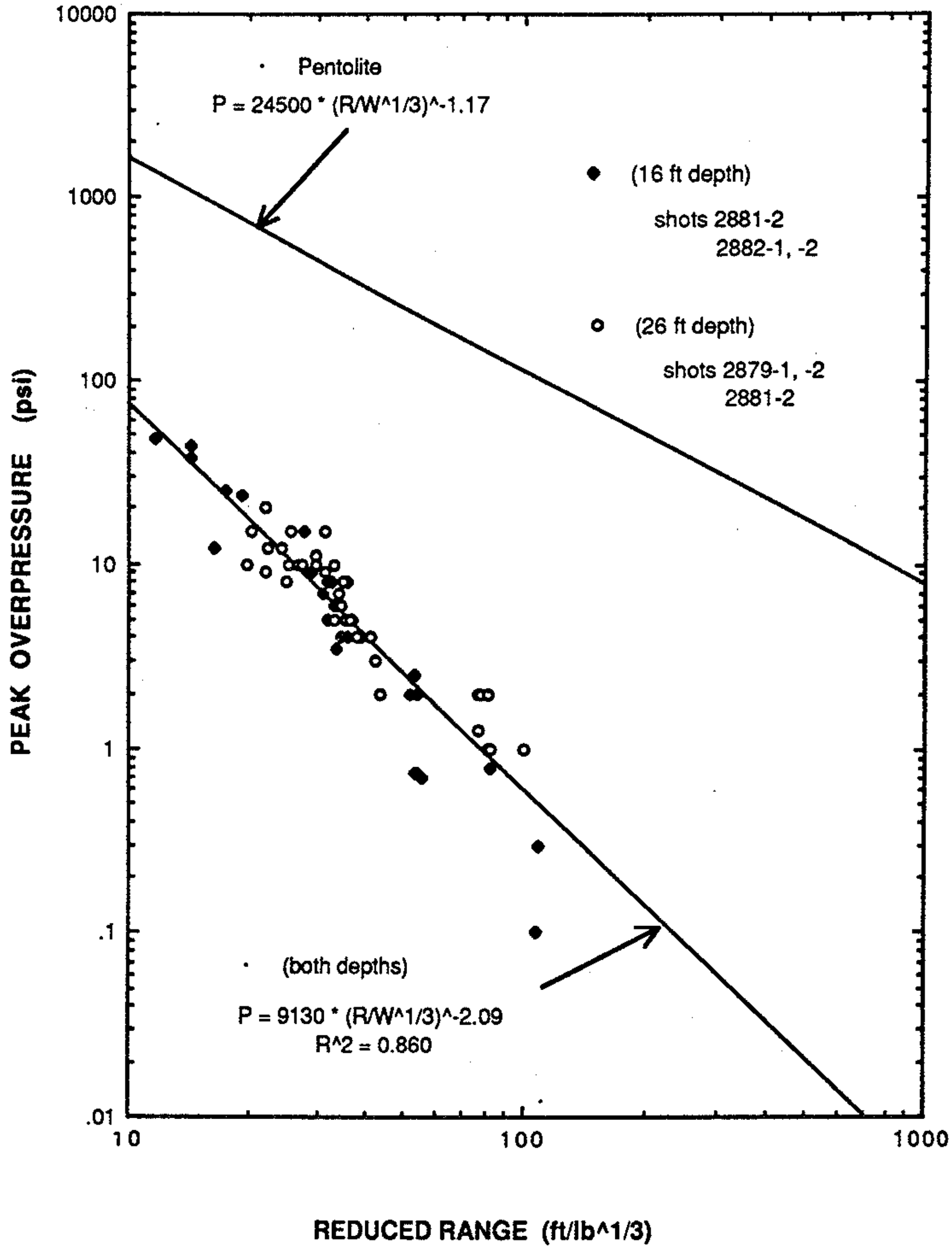


FIGURE 5-9. BUBBLE SHOCK OVERPRESSURE FROM SKIRT PILES (16- AND 26-FOOT CHARGE DEPTHS)

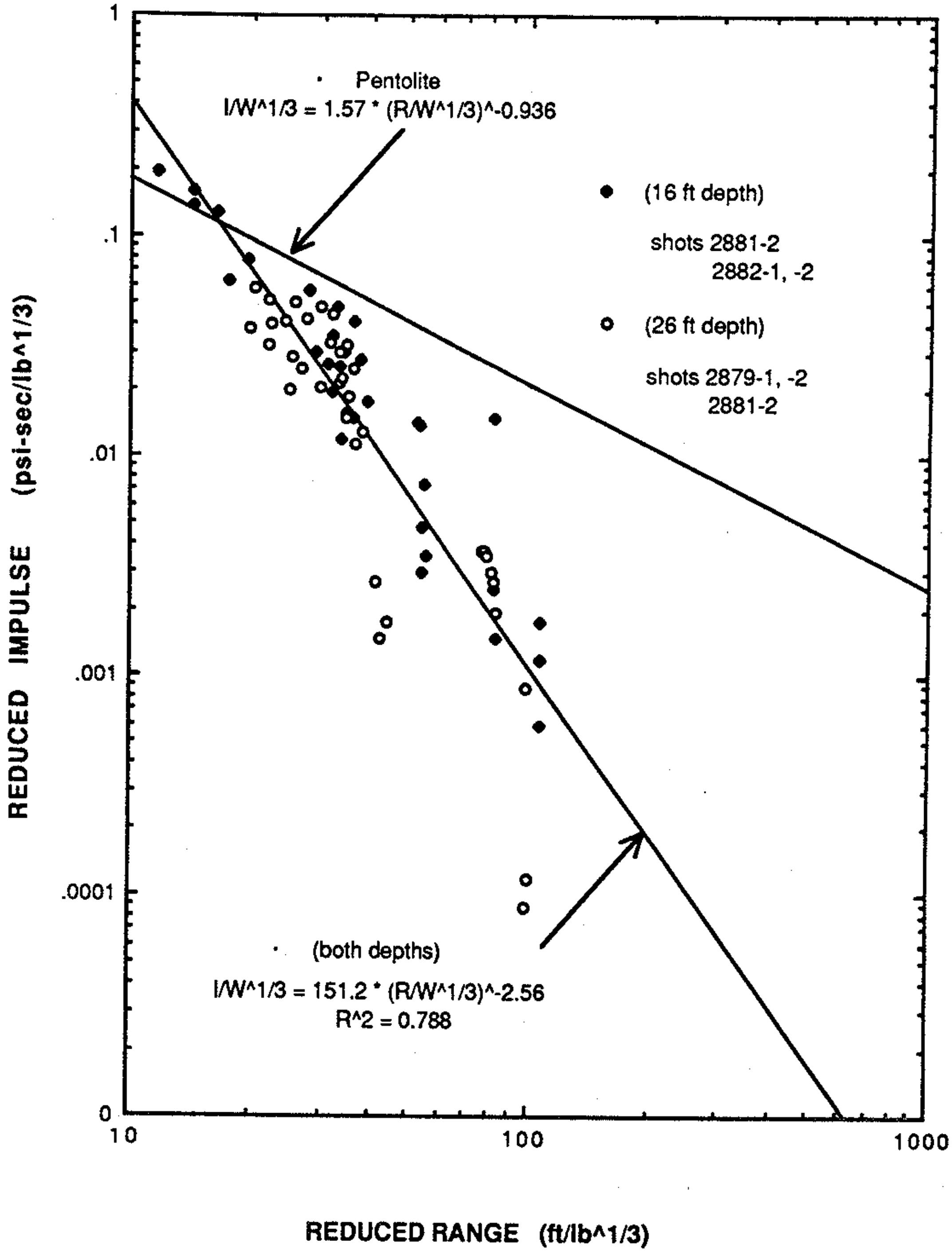


FIGURE 5-10. BUBBLE SHOCK IMPULSE FROM SKIRT PILES
(16- AND 26-FOOT CHARGE DEPTHS)

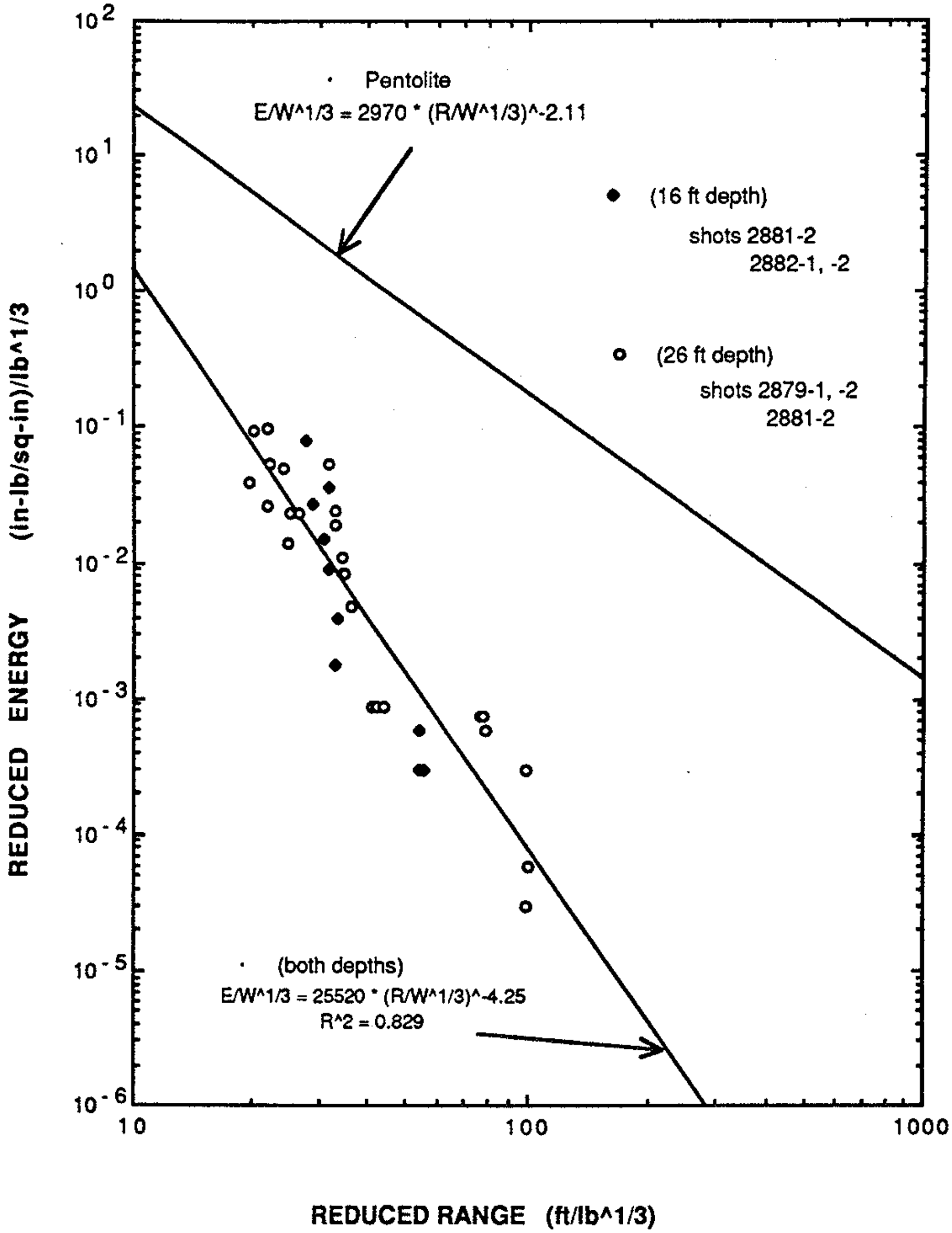


FIGURE 5-11. BUBBLE SHOCK ENERGY FROM SKIRT PILES (16- AND 26-FOOT CHARGE DEPTHS)

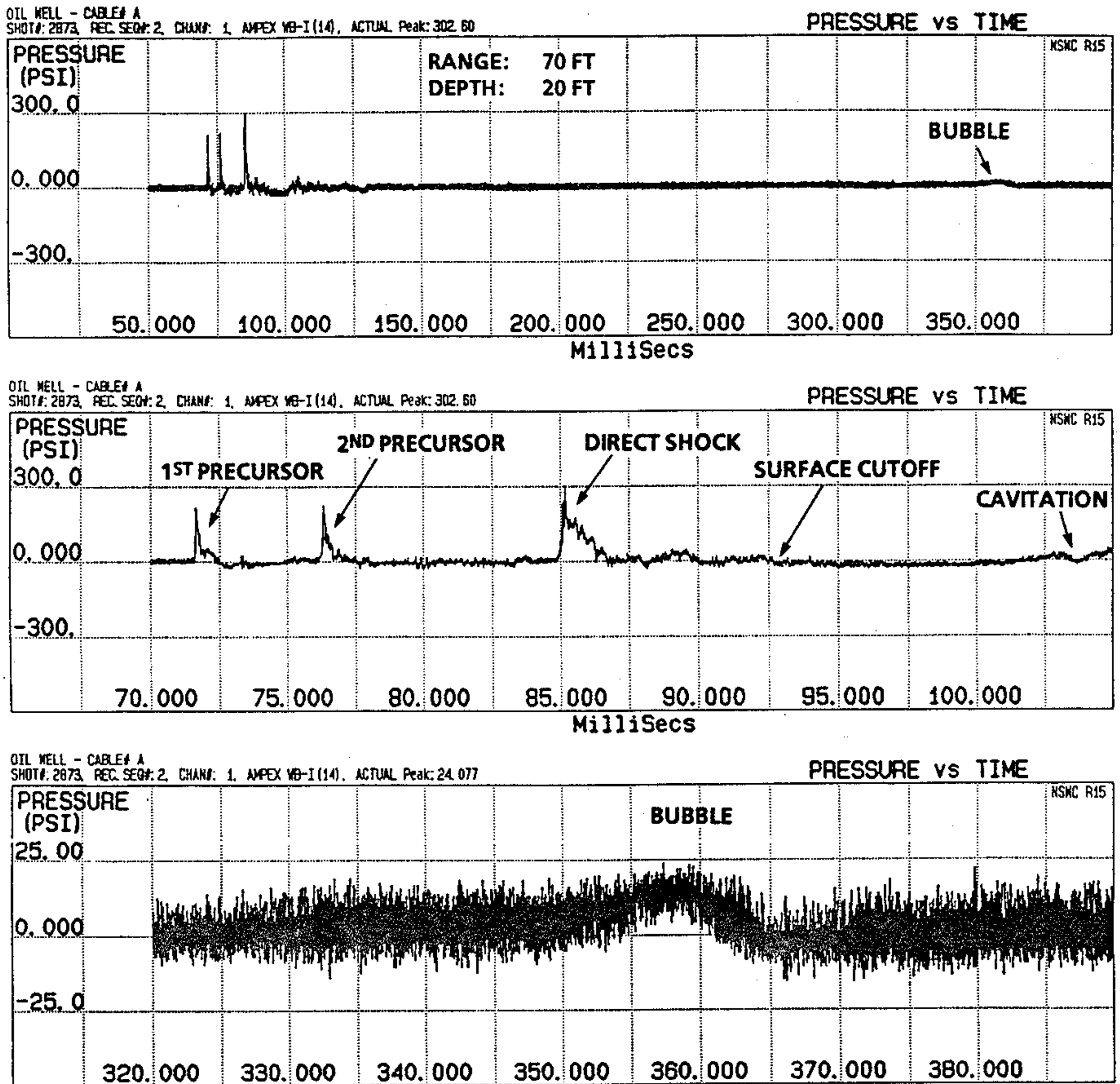


FIGURE 5-12. WATER VENTED WELL CONDUCTOR PRESSURE RECORDS (TOP GAUGE AT FIRST STATION)

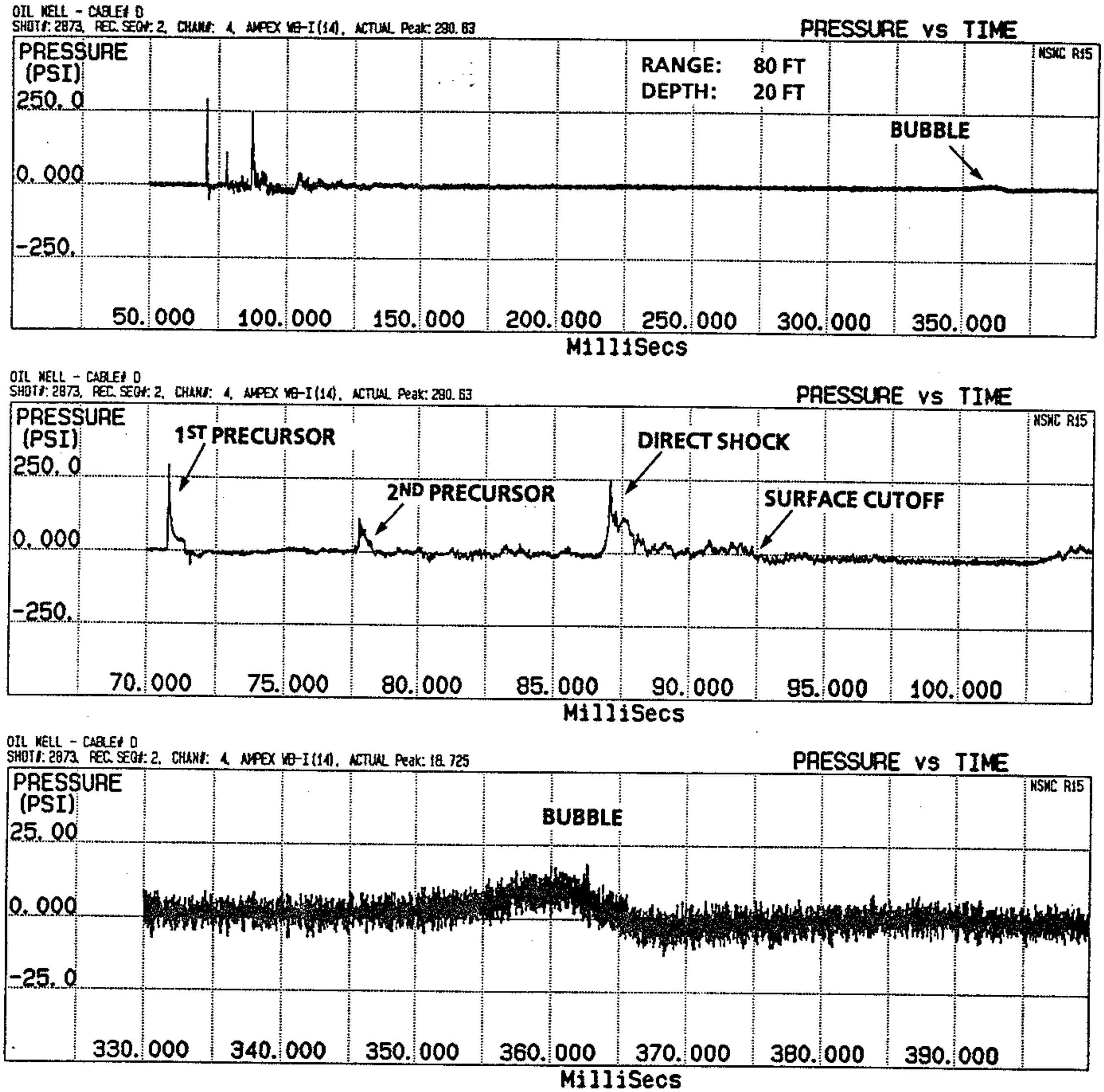


FIGURE 5-13. WATER VENTED WELL CONDUCTOR PRESSURE RECORDS
(TOP GAUGE AT SECOND STATION)

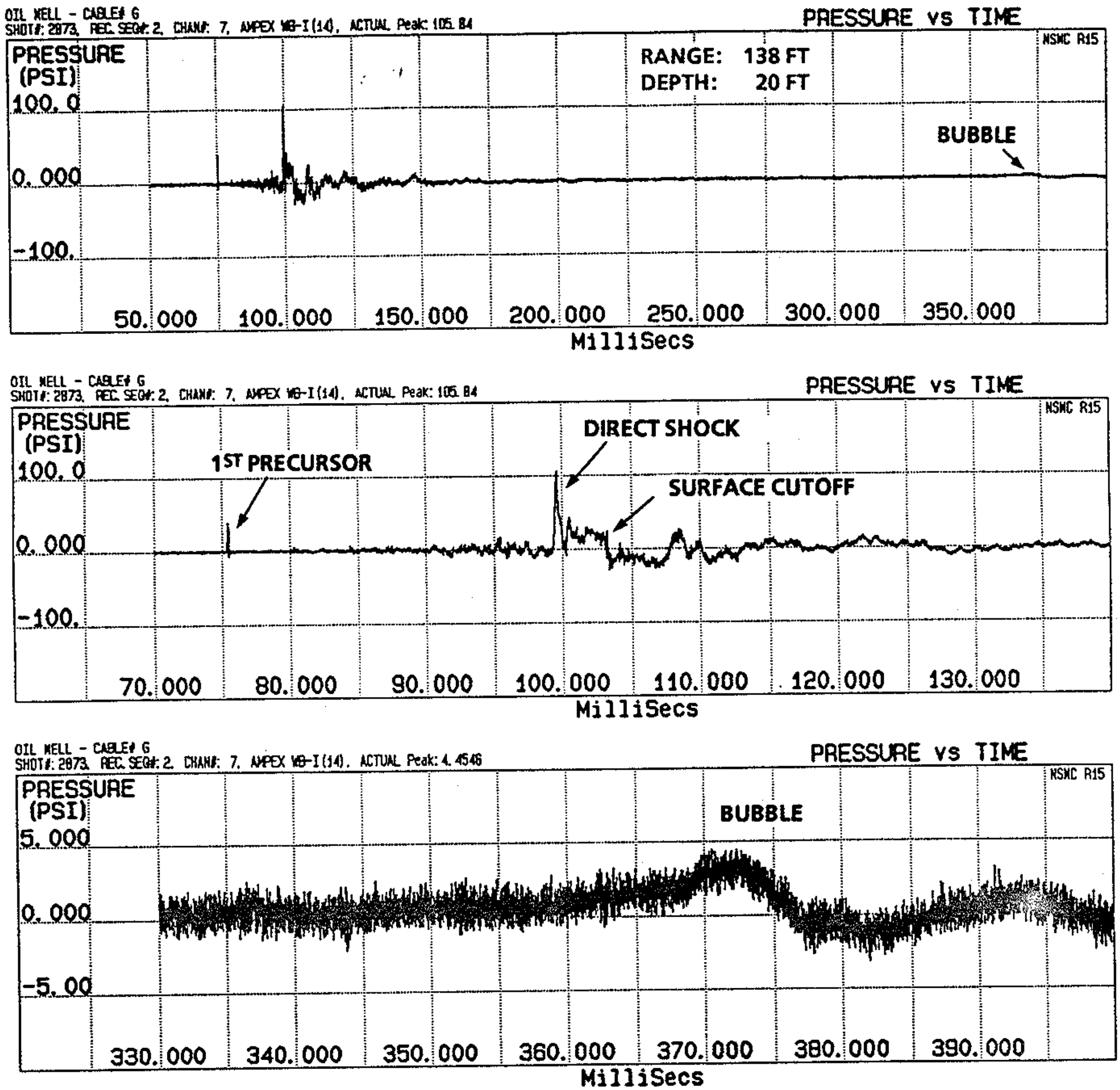


FIGURE 5-14. WATER VENTED WELL CONDUCTOR PRESSURE RECORDS
(TOP GAUGE AT THIRD STATION)

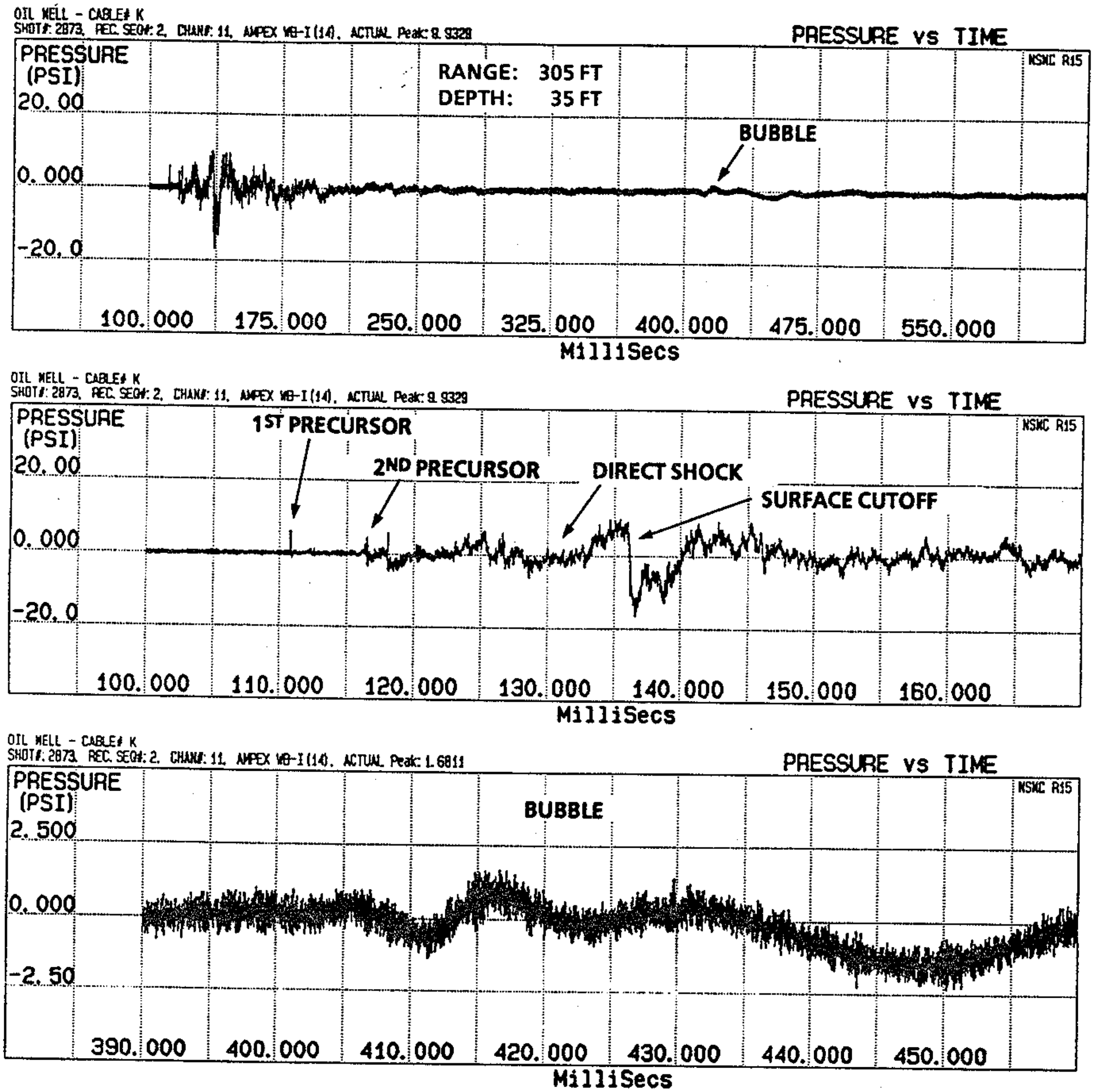


FIGURE 5-15. WATER VENTED WELL CONDUCTOR PRESSURE RECORDS
(TOP GAUGE AT FOURTH STATION)

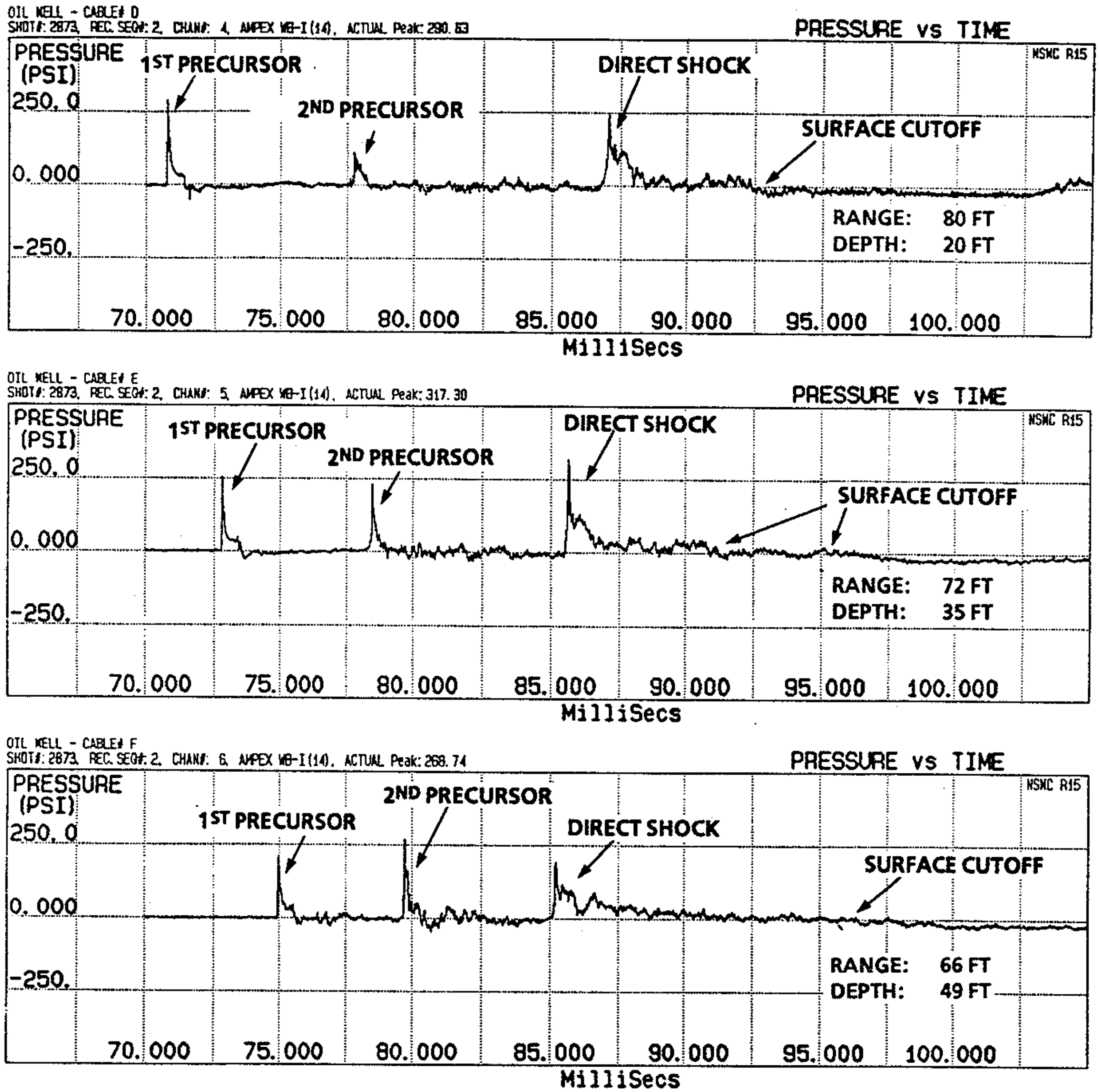


FIGURE 5-16. WATER VENTED WELL CONDUCTOR PRESSURE RECORDS (PRECURSOR AT SECOND STATION)

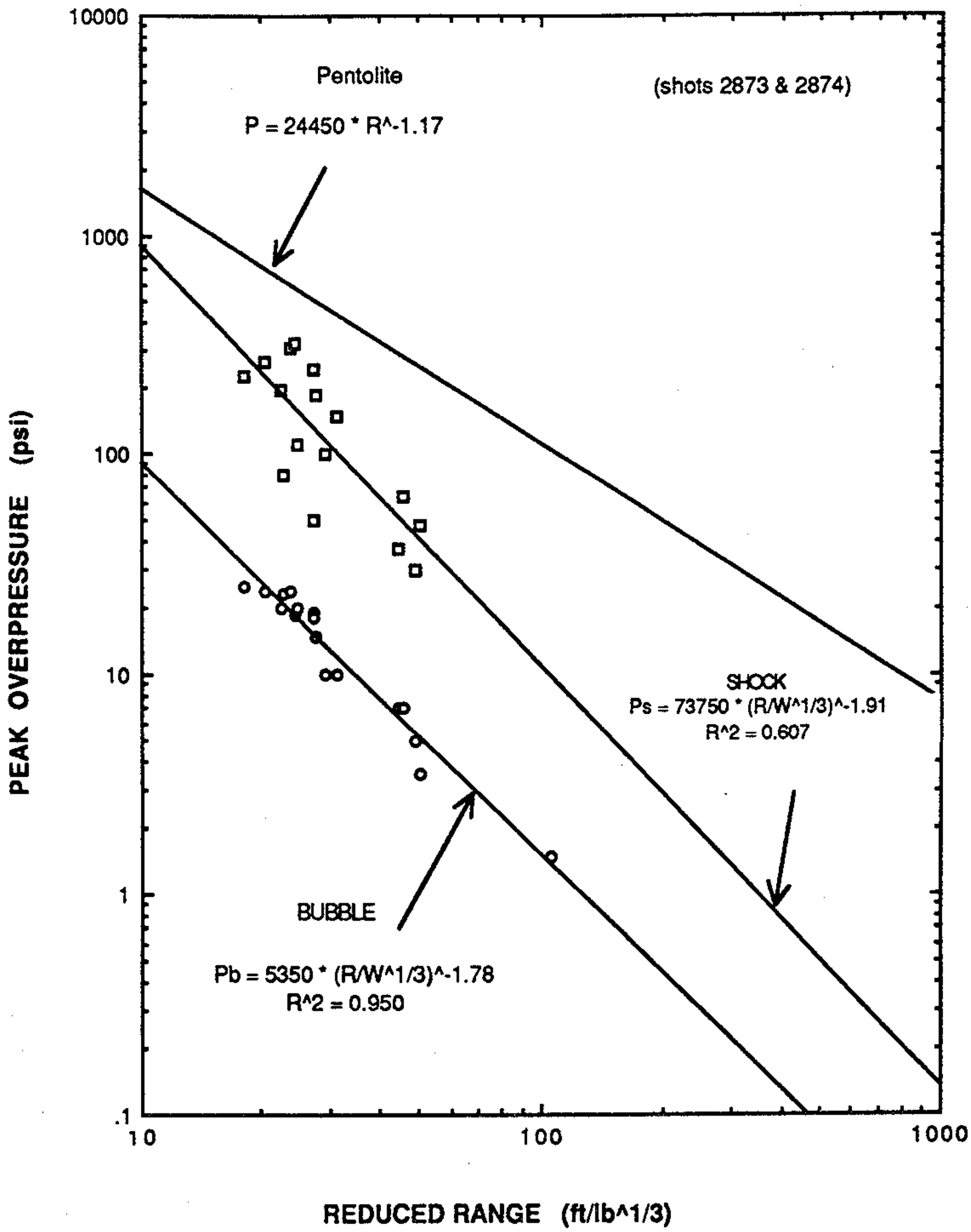


FIGURE 5-17. SHOCK OVERPRESSURE FROM WELL CONDUCTORS (UNDERWATER STUBS)

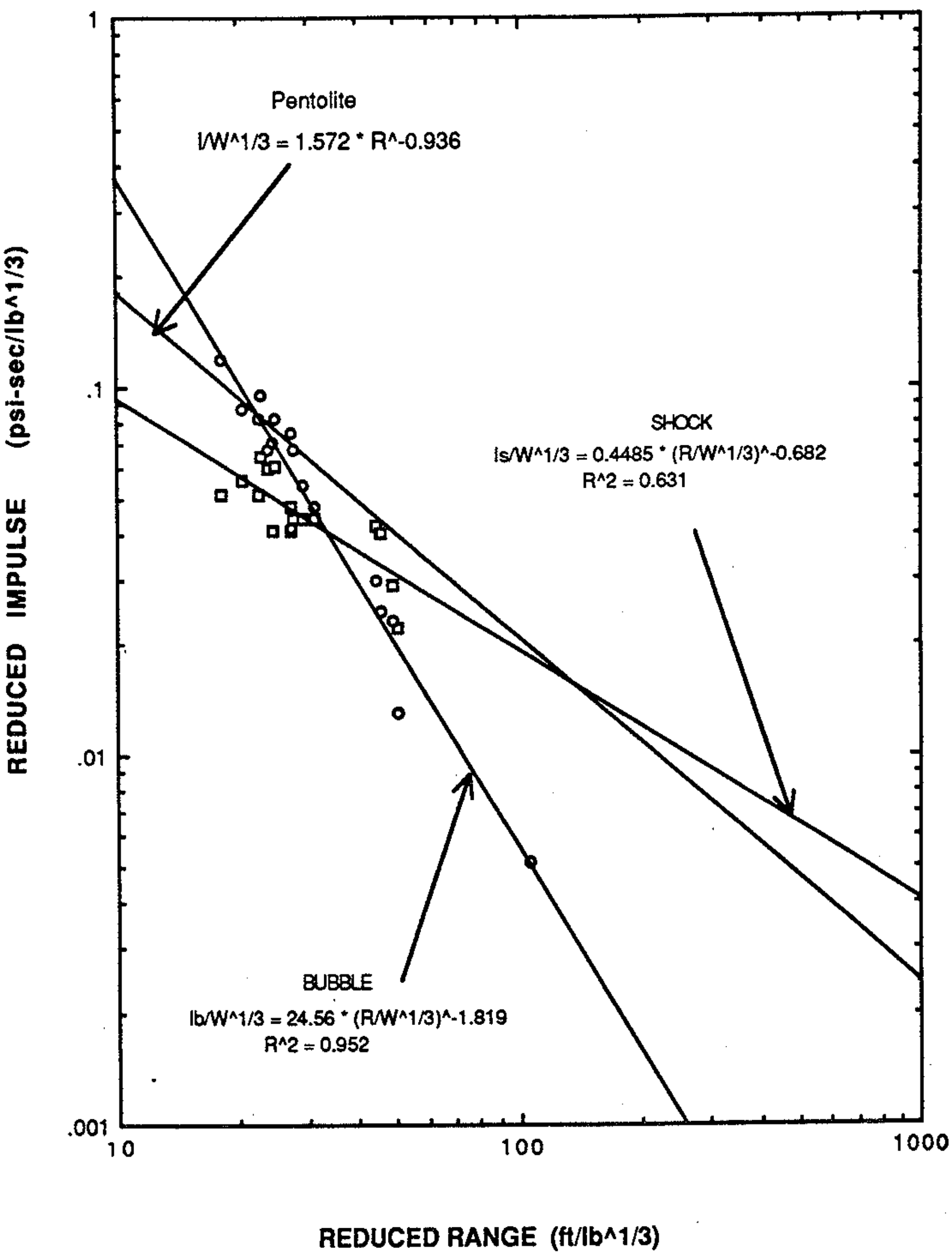


FIGURE 5-18. SHOCK IMPULSE FROM WELL CONDUCTORS (UNDERWATER STUBS)

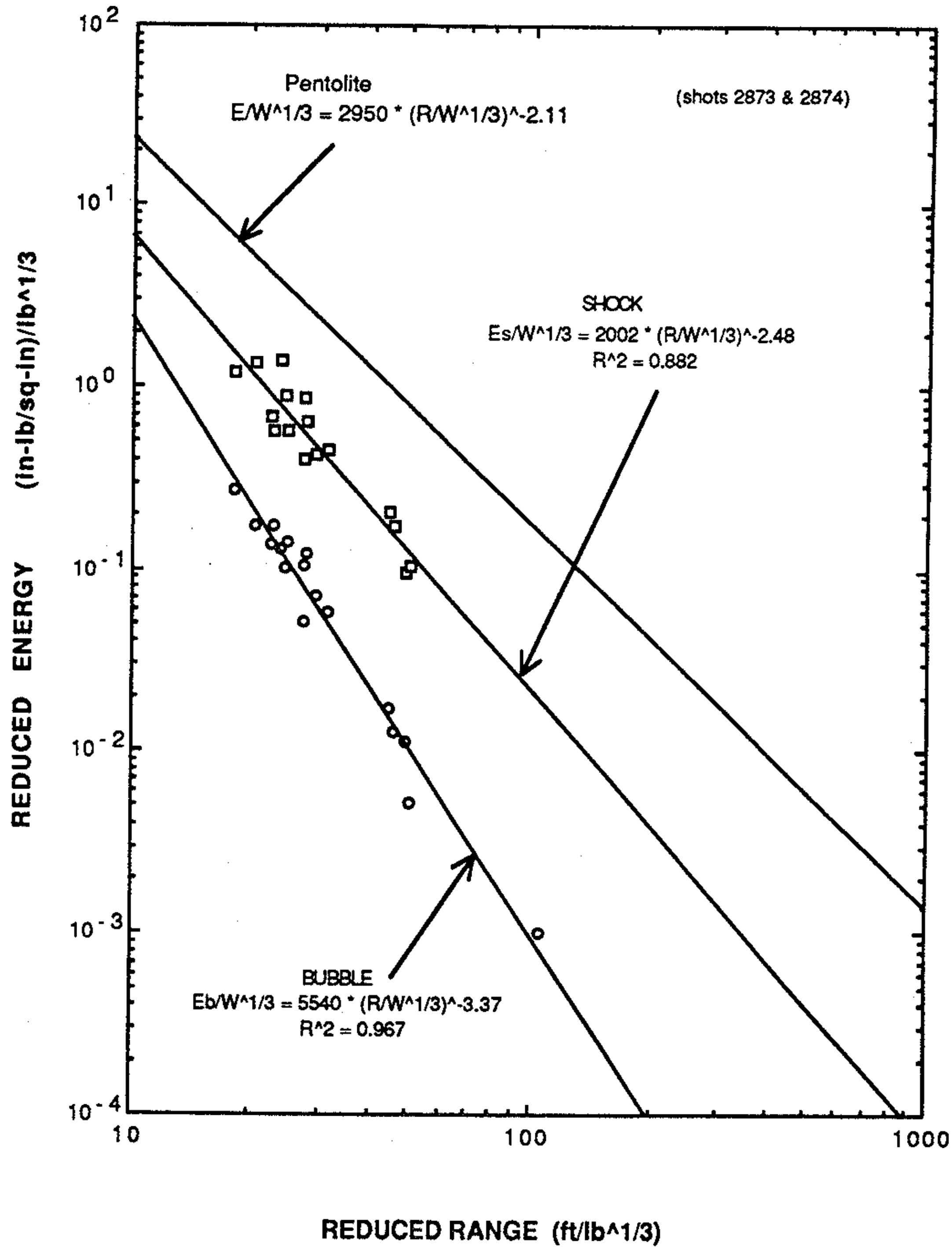


FIGURE 5-19. SHOCK ENERGY FROM WELL CONDUCTORS (UNDERWATER STUBS)

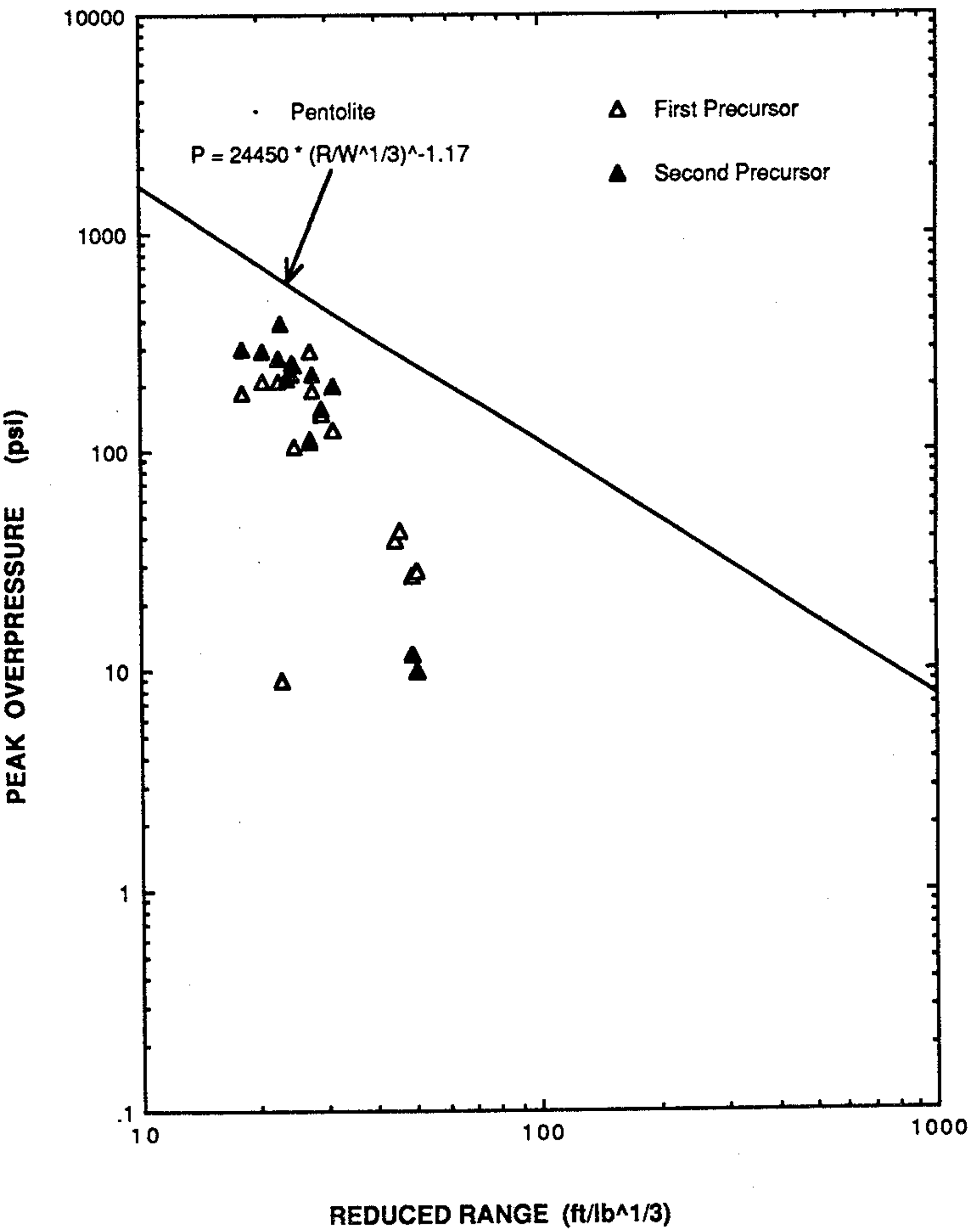


FIGURE 5-20. PRECURSOR SHOCK OVERPRESSURE FROM WELL CONDUCTORS (UNDERWATER STUBS)

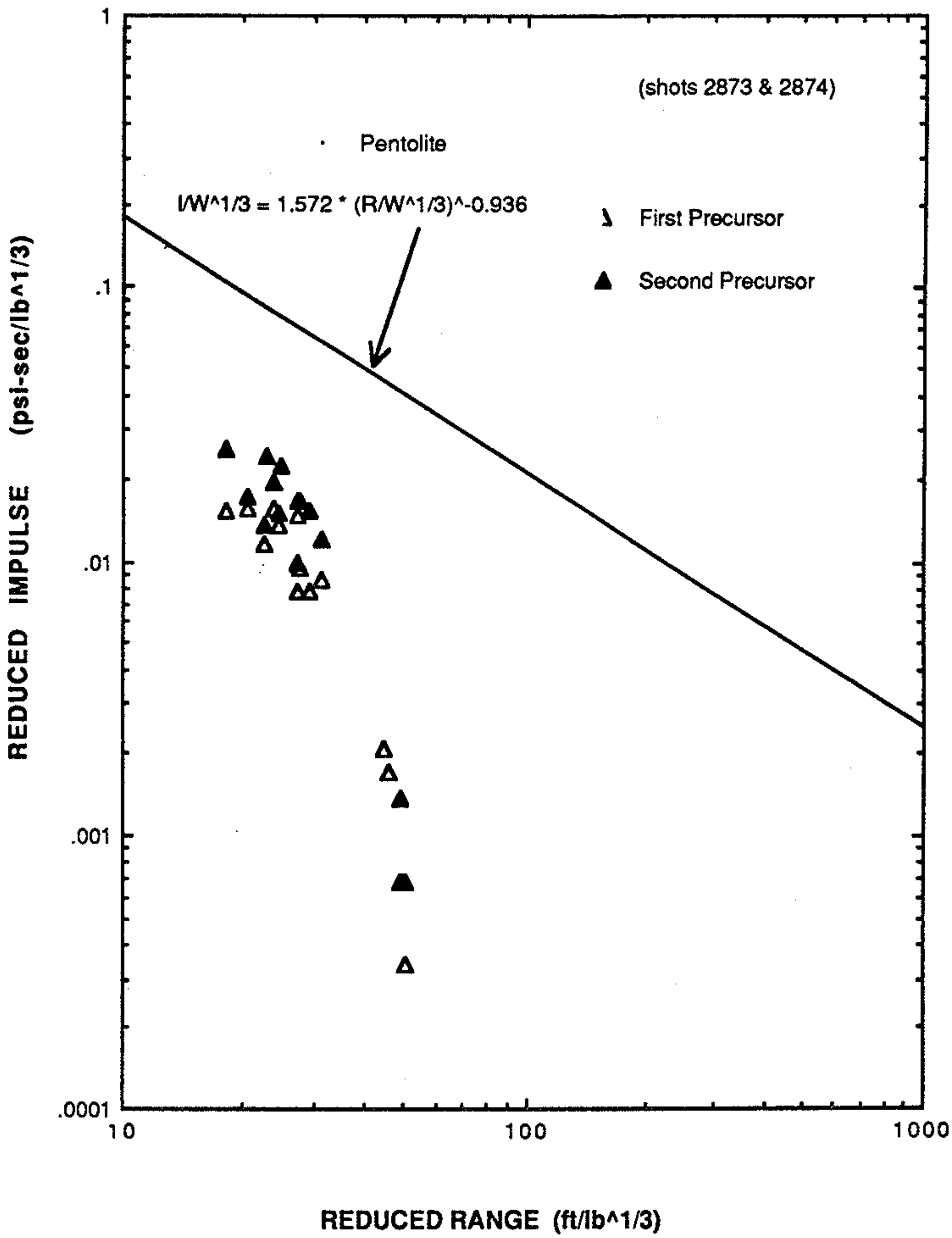


FIGURE 5-21. PRECURSOR IMPULSE FROM WELL CONDUCTORS (UNDERWATER STUBS)

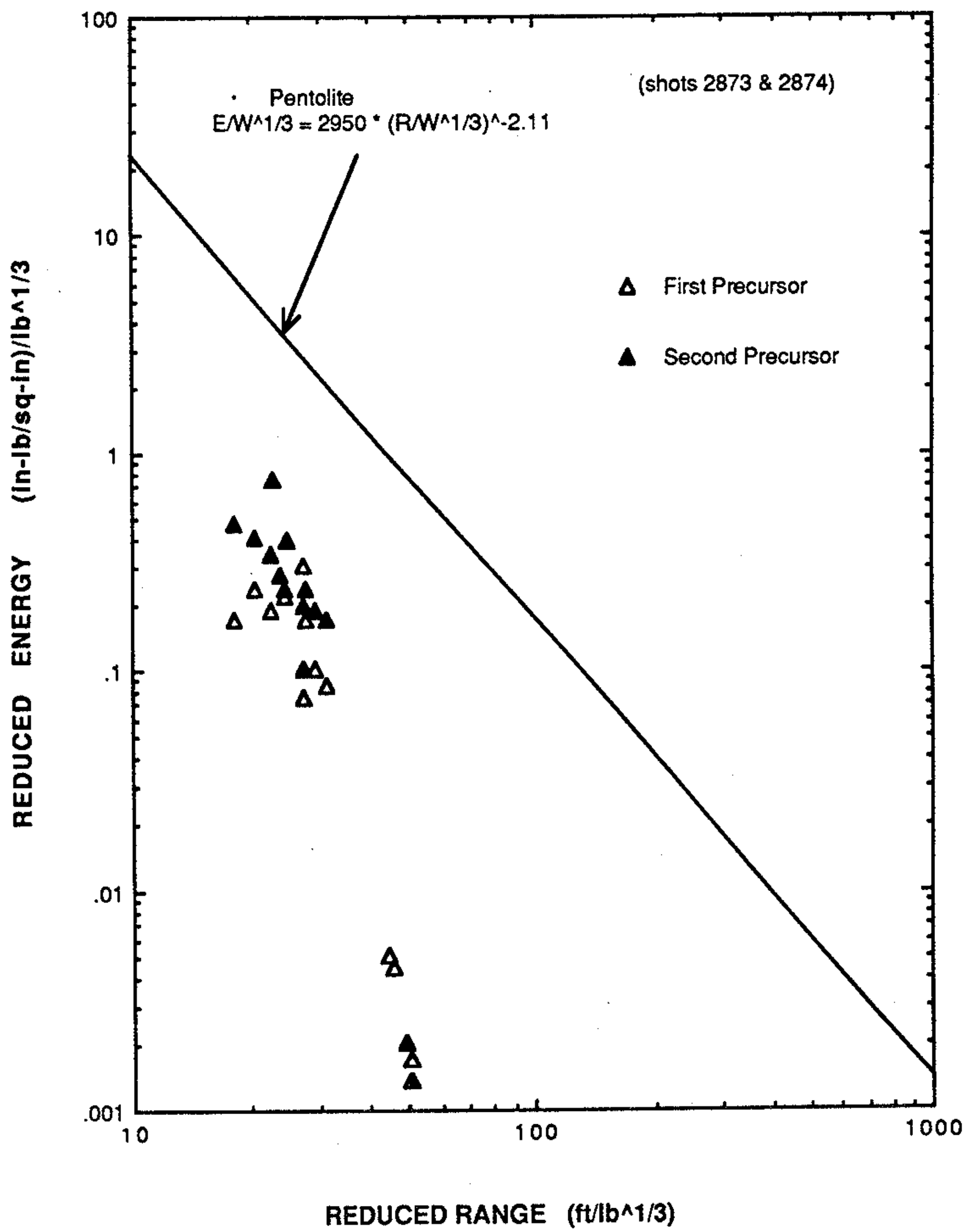


FIGURE 5-22. PRECURSOR ENERGY FROM WELL CONDUCTORS (UNDERWATER STUBS)

TABLE 5-1. BUBBLE PERIODS AND SURFACE CUTOFF TIMES
(Skirt Piles)

Shot	Gauge	First Precursor Lead Time (msec)	Direct Shock Cutoff Times*		Late Pulse (msec)	Pentolite Bubble Period (msec)
			Observed (msec)	Predicted (msec)		
2879-1	A	5.9	5.4	6.0	241	260
	B	4.1	8.7	10.3	240	
	C	2.6	11.4	14.2	244	
	D	5.9	4.5	6.3	240	
(26-ft burial	E	4.0	9.0	10.8	239	
depth)	F	2.8	12.0	14.8	242	
	G	5.0	4.9	6.3	237	
	H	3.5	8.1	10.9	239	
	I	2.4	10.7	15.0	240	
	J	3.8	2.5	2.3	242	
	K	3.4	3.4	4.1	242	
	L	2.5	5.0	5.7	245	
2882-1	A	7.0	7.8	7.2	277	260
	B	4.5	13.5	12.3	270	
	C	1.8	16.5	16.7	274	
	D	6.8	7.5	6.7	278	
(16-ft burial	E	3.8	12.0	11.5	279	
depth)	F	1.6	13.2	15.6	276	
	G	4.4	8.2	4.4	275	
	H	2.8	10.9	7.7	276	
	I	1.4	12.0	10.4	277	
	J	2.9	2.6	1.9	278	
	K	2.5	3.6	3.4	278	
	L	3.0	3.3	4.7	276	

*All times are measured from the arrival of the direct shock pulse.

TABLE 5-2. BUBBLE PERIODS AND SURFACE CUTOFF TIMES
(Submerged Well Conductors)

Shot	Gauge	First Precursor Lead Time (msec)	Direct Shock Cutoff Times*		Late Pulse (msec)	Pentolite Bubble Period (msec)
			Observed (msec)	Predicted (msec)		
2873	A	13.6	5.0	6.6	269	260
	B	9.9	7.8	11.3	268	
	C	7.1	15.0	15.3	268	
	D	16.0	5.7	6.0	269	
	E	12.7	10.0	10.2	270	
	F	10.2	11.2	13.8	272	
	G	23.8	4.0	3.8	268	
	H	21.6	6.5	6.6	270	
	I	19.6	7.8	9.1	271	
	J	--	--	--	--	
	K	--	--	--	--	
	L	--	--	--	--	
2874	A	12.5	6.0	5.9	259	260
	B	9.7	9.5	10.1	253	
	C	12.9	12.0	13.7	258	
	D	19.8	5.3	5.4	258	
	E	16.7	8.8	9.2	252	
	F	16.0	10.3	12.5	253	
	G	21.2	3.4	3.6	256	
	H	19.1	6.1	6.2	254	
	I	--	--	--	--	
	J	--	--	--	--	
	K	--	--	--	--	
	L	--	--	--	--	

*All times are measured from the arrival of the direct shock pulse.

CHAPTER 6

DISCUSSION

SUMMARY

In December 1988 Exxon's West Delta Block 30 platform was removed from a point 10 miles south of New Orleans, Louisiana, in the Gulf of Mexico Federal offshore waters. A total of 35 bottom penetrating tubular members were explosively severed and removed from the floor of the Gulf. Twenty-six of the detonations were monitored by NAVSWC personnel. Shock overpressure, impulse, and energy were measured to generate the direct knowledge of the shock effects of such explosions.

All detonations produced a "direct" shock–identified by the presence of a surface cutoff dip on the pressure-time records. Many were preceded by at least one "precursor" and followed by smaller cavitation and bottom reflection bumps. Many were followed at several hundred milliseconds by a "late" pulse that was associated with the collapse of the explosion product gas bubble. The times at which the late pulses occurred coincide with bubble periods determined from archival data for Pentolite charges of the same weights as those fired to sever the platform tubulars.

Measurements were made at reduced ranges from about 10 to about 100 ft/lb$^{1/3}$. At the maximum range of 100 ft/lb$^{1/3}$ (about 400 feet from a 50-pound charge) each of the parameters had dropped to about 10 percent of the values predicted by using free water Pentolite data. Least square curves were fitted to each class of data, and these can be used to predict values that may be expected at greater than 400-foot ranges– with the understanding that there is no actual data at the larger ranges.

Pressure, impulse, and energy in the direct shock were, in general, greater than the same quantities measured on the precursor and the bubble pulses. Perhaps surprising was the observation that the relatively low amplitude bubble pulse produces impulse and energy often equivalent to that produced by the direct shock. This is reasonable in view of the longer duration of the bubble pulse.

Conservative predictions for other platform removal operations can be made from existing free water Pentolite data. Values calculated from the Pentolite data are expected to be an order of magnitude higher than would actually be observed at ranges greater than 400 feet for charges up to 50 pounds.

In addition to the differing properties of the various tubular elements, several variations in conditions were examined. First, the location of the top of the (hollow) tubular influences the number of pulses observed. Second, using charge weights between 25 and 50 pounds had no noticeable effect on the amplitudes of the shock waves propagated into the water. Third, the depth of charge burial beneath the mud interface (in the range of 8 to 26 feet for 25- to 50-pound charges) appears to have little effect on shock pressure amplitudes (or impulse or energy, for that matter).

Shock wave measurements during the platform removal operation are consistent with measurements made during a controlled half-scale series of tests performed in the early eighties in the Potomac River at Dahlgren, Virginia. Gauges on the half-scale tests were located at much closer ranges than were those on the platform removal shots. Measurements agree where the ranges overlap.

AIR/WATER TERMINATION

Pressure, impulse, and energy for the direct shock produced by both air- and water-terminated well conductor severance shots are compared in Figures 6-1 to 6-3. Figures 6-4 to 6-6 compare pressure, impulse, and energy for the bubble shock on the same shots. The comparison is between the two conductors whose tops were 45 feet underwater with the several conductors whose tops terminated in the air above the water surface.

For the direct shock, overpressure and energy appear indistinguishable. However, as shown in Figure 6-2, impulse from the water-terminated conductor detonations is somewhat lower than those from the detonations in the air-vented conductors.

Direct Shock Similitude Equations
(Well Conductors)

Pressure: $P = 49260\,(R/W^{1/3})^{-1.81}$

Reduced Impulse: $I/W^{1/3} = 37.41\,(R/W^{1/3})^{-1.89}$

Reduced Energy Flux: $E/W^{1/3} = 52330\,(R/W^{1/3})^{-3.40}$

(These equations were fitted to the data obtained from the air-terminated conductors since the measurements were grouped more tightly and extended over a longer range than the data for the water-terminated stubs.)

For the bubble shock, the two 25-pound shots (one terminated in air, one terminated underwater) mingle indistinguishably. The 50-pound shots (top terminated underwater) fall lower. This is probably because the conductor in question was of more substantial construction, as mentioned in Chapter 4. Because of the large scatter in these measurements, no similitude equations were derived for the bubble results.

For the two submerged well conductor shots, two precursors were observed. Some of these pulses had amplitudes equivalent to those of the direct shock, but many of the precursor amplitudes were insignificant relative to the direct shock. Because the precursors had short durations, the impulse and energy carried by them were negligible relative to the direct shock impulses and energies.

A single precursor was observed on the (less deeply submerged) skirt pile shots, as well as on most other shots. The single precursors had amplitudes, durations, impulse, and energy similar to the double precursors just described.

The precursor pulse origins were not identified. However, from consideration of their arrival times, they all seemed to originate near the water surface.

EFFECT OF CHARGE PLACEMENT DEPTH

Within the precision of the data, there was no difference between the pressure pulses observed near the main pile detonations with the charges at depths of 8, 16, and 26 feet below the mud line. Similarly, there was no significant difference noted between the pressure pulses observed near the skirt pile detonations for which the charge depths were 16 and 26 feet below the mud line.

Direct Shock Similitude Equations
(Main Piles)

Pressure: $P = 75160\,(R/W^{1/3})^{-1.93}$

Reduced Impulse: $I/W^{1/3} = 15.35\,(R/W^{1/3})^{-1.79}$

Reduced Energy Flux: $E/W^{1/3} = 11900\,(R/W^{1/3})^{-3.13}$

(These equations were fitted to the data obtained from the detonations in the main piles that were jetted to allow charge placement 16 feet below the mud line. The numerical values are shown in Figures 4-32, 4-33, and 4-34, where it is seen that the data from the 8- and 26-foot charge burial depths cluster about the same line fits.)

NEGATIVE PRESSURES

Pressures less than ambient were observed following the direct shock pulses on most shots. These negative pressure amplitudes seldom dipped below -40 psi, and the pulses had durations of several milliseconds.

PAST WORK COMPARISONS

Several controlled tests were conducted in the Potomac River in the early 1980's. Simulated half-scale well conductors were implanted in the river bottom mud. A relatively dense array of underwater pressure gauges was deployed at closer ranges than were possible on the tests in the Gulf of Mexico. The simulated conductors were severed with cylindrical Composition C-4 charges.

Peak pressures from these shots are plotted versus reduced range on Figure 6-7. Also on this figure are the peak overpressures observed near the air-vented well conductors removed from the West Delta 30 platform. The two sets of data do not overlap in range, but they are obviously in agreement despite the different explosives used.

Impulse and energy from the half-scale shots fall below the lines fitted to the platform data shown on Figures 6-8 and 6-9. This difference is reasonable because impulse and energy time integrals were taken only to 1 millisecond, while those for the platform removal shots were continued to the surface cutoff pulse. The cutoff pulses arrived at various times ranging from 2 to about 20 milliseconds. (This does not imply a factor of 2 to 20 between the impulse/energy integrals because at later times the shock pressure is much lower than the initial peak pressure.)

FUTURE WORK

Extension and Verification

Future platform removal operations should be monitored for several reasons:

- to verify the results and conclusions of this effort
- to establish the applicability of these results:
  - to platforms removed from deeper water
  - to platforms with different pile configurations (grouting systems and amount of steel may vary)
  - to charges of different size, shape, and explosive (shaped charge effects should be examined)

Gauge Location

Data scatter can be reduced considerably if the gauge positions are known more accurately. The gauges can be located by exercising the NAVSWC ranging program. This would entail firing a small charge at a known location after deploying the gauge rig and just prior to detonating the severance charge(s). The charge must have a fiducial gauge mounted on it so that the ranging program can be used. It need not be mounted on the platform subject to removal but its location must be known relative to the platform and gauges.

Cavitation

On this series of tests, care was taken to avoid mounting gauges in the cavitation layer just below the air/water interface. Signals from gauges in this layer can be rather difficult to interpret. The layer can be 20 feet thick and can extend as much as 1000 feet from a point on the water surface directly above the detonation.

Pressure pulses in the cavitation layer should be examined. They are not expected to produce significant damage to mechanical objects, though they may have a minor effect on biological organisms that may be just below the surface when a severance charge is fired.

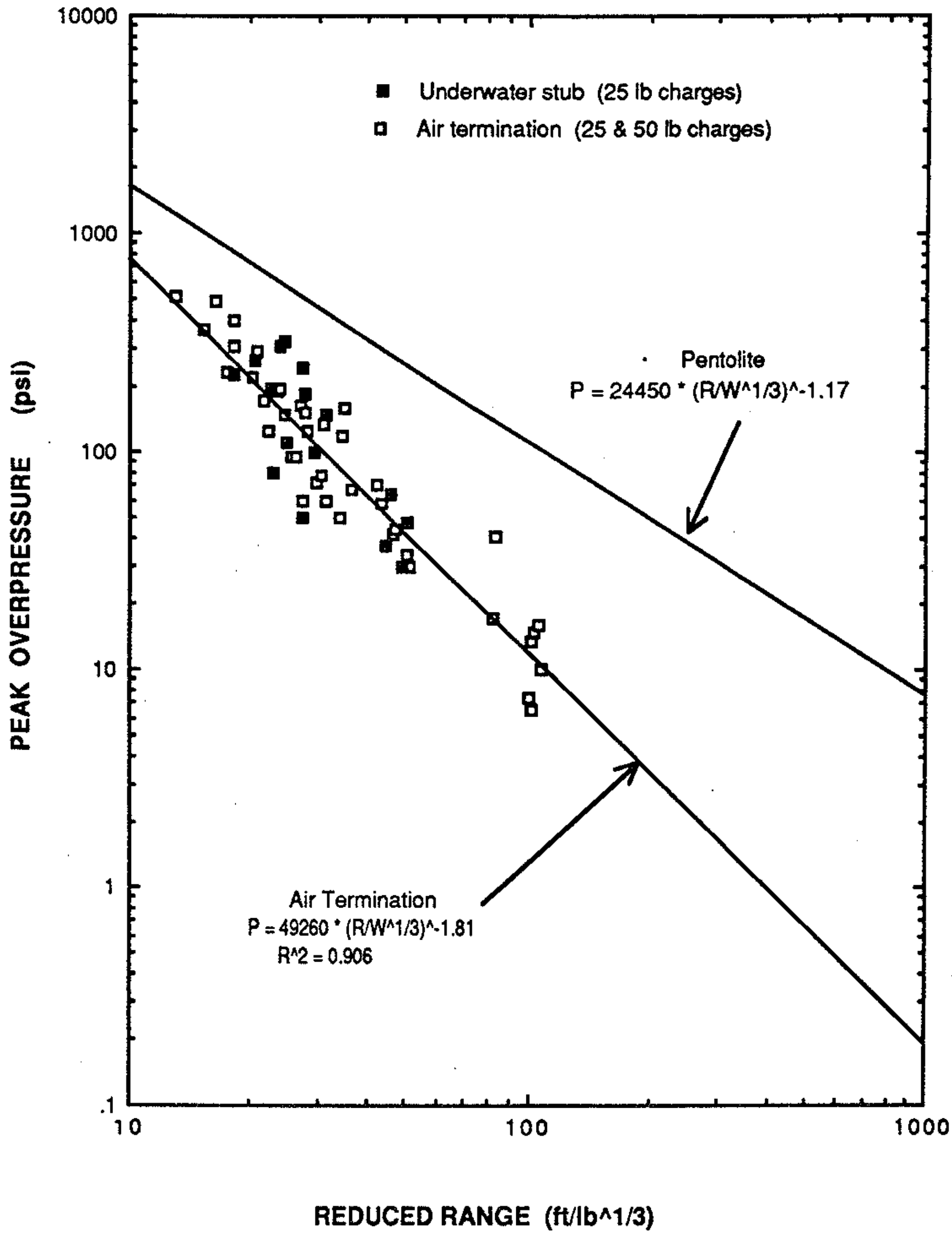


FIGURE 6-1. DIRECT SHOCK OVERPRESSURE FROM WELL CONDUCTORS

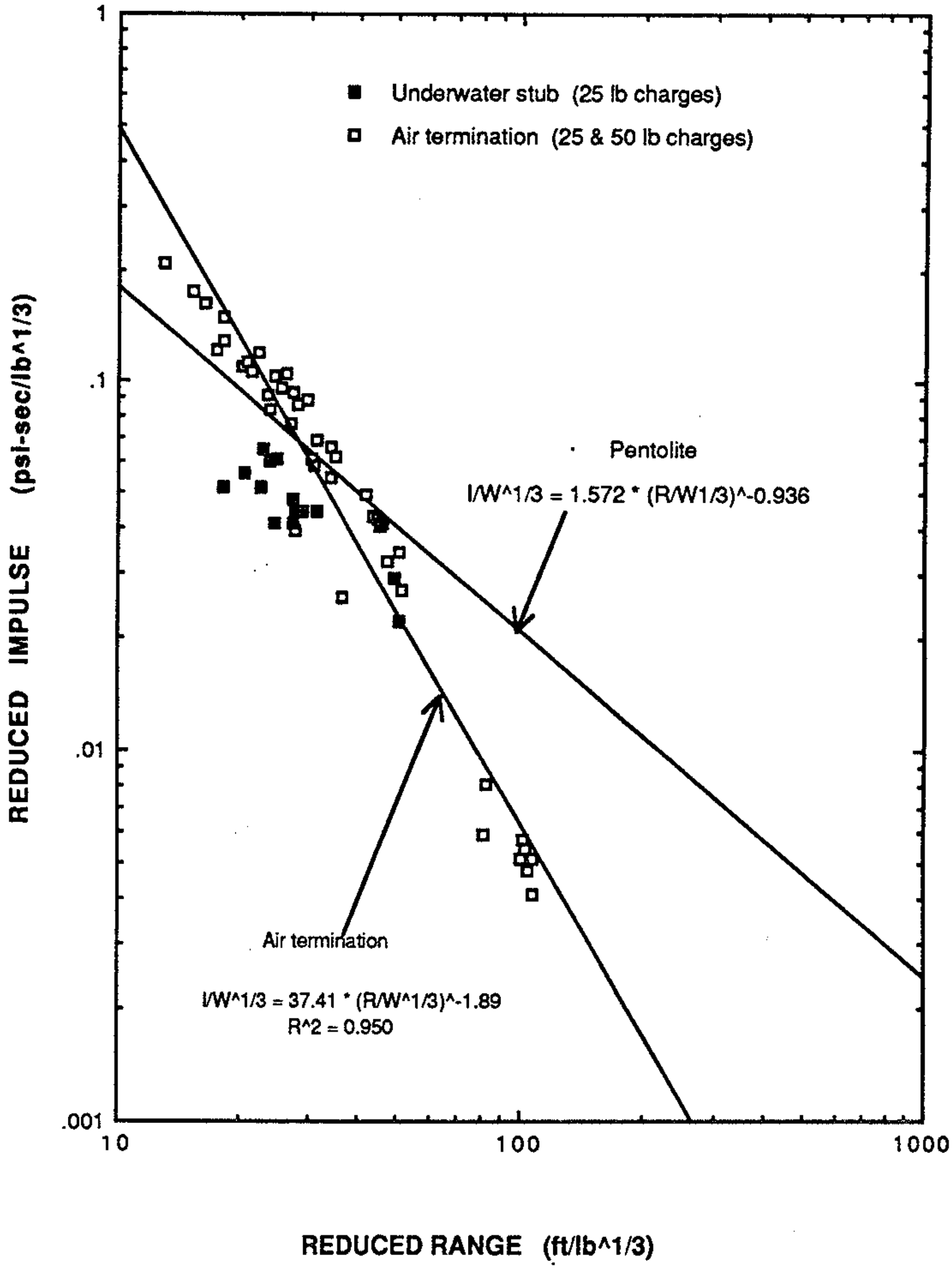


FIGURE 6-2. DIRECT SHOCK IMPULSE FROM WELL CONDUCTORS

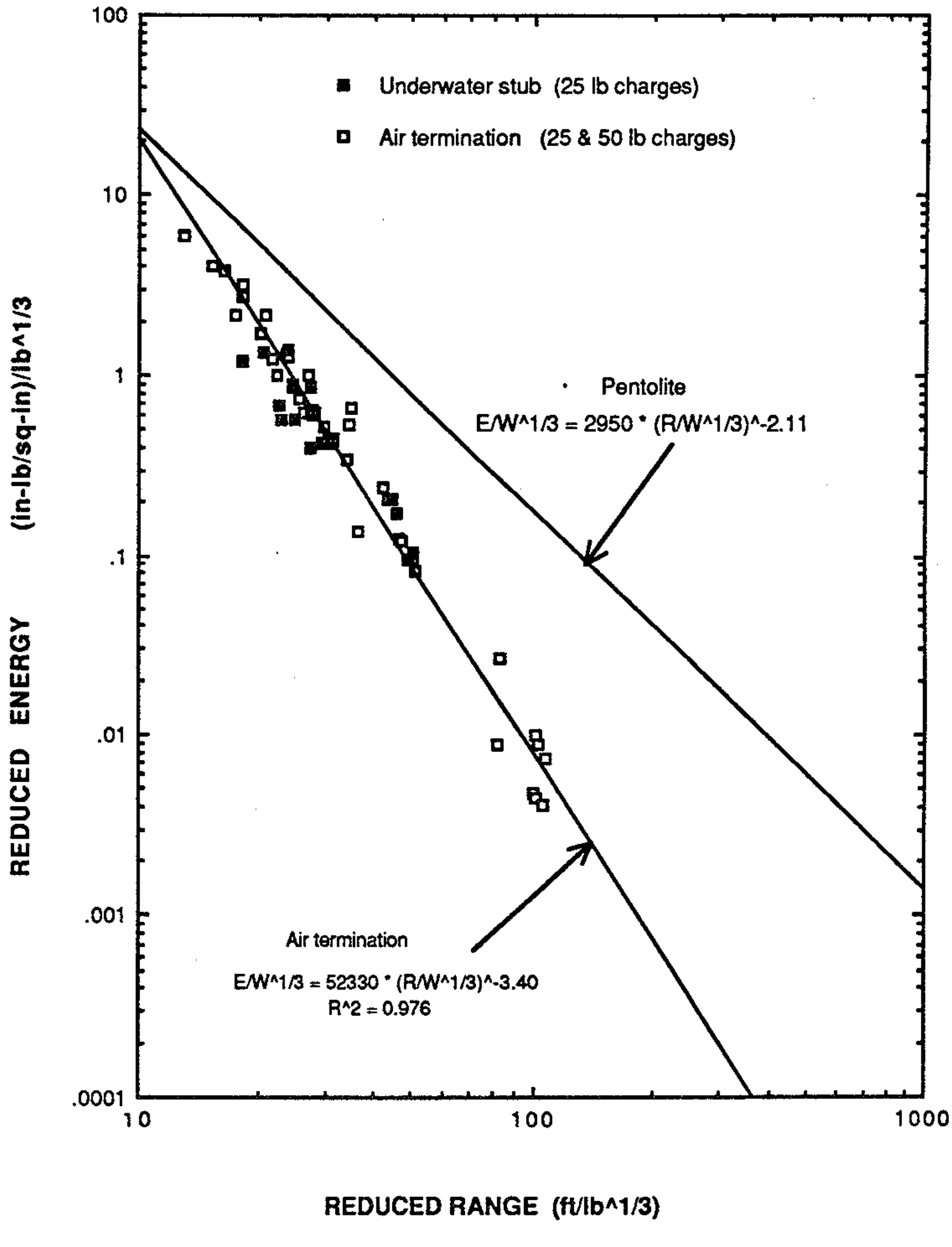


FIGURE 6-3. DIRECT SHOCK ENERGY FROM WELL CONDUCTORS

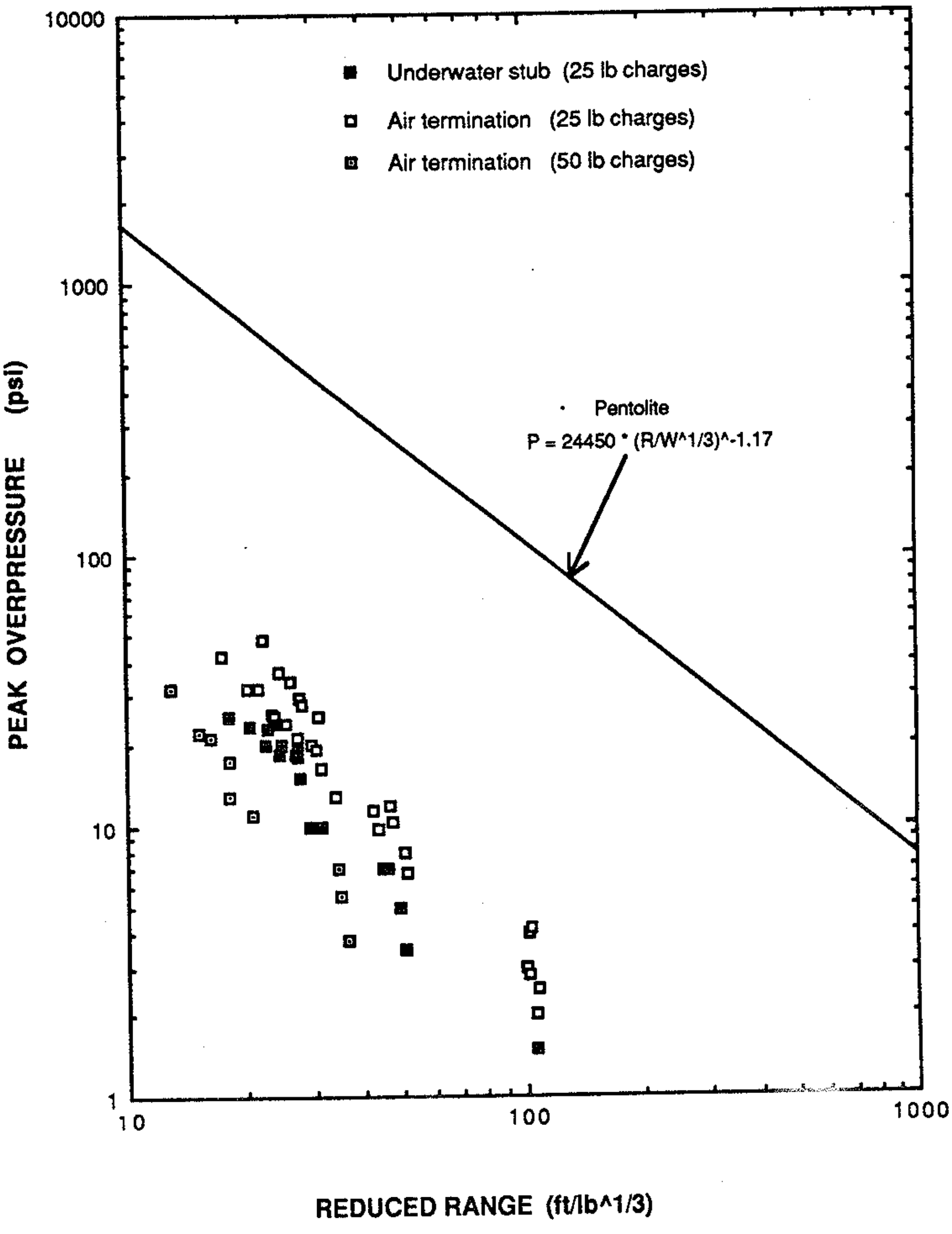


FIGURE 6-4. BUBBLE SHOCK OVERPRESSURE FROM WELL CONDUCTORS

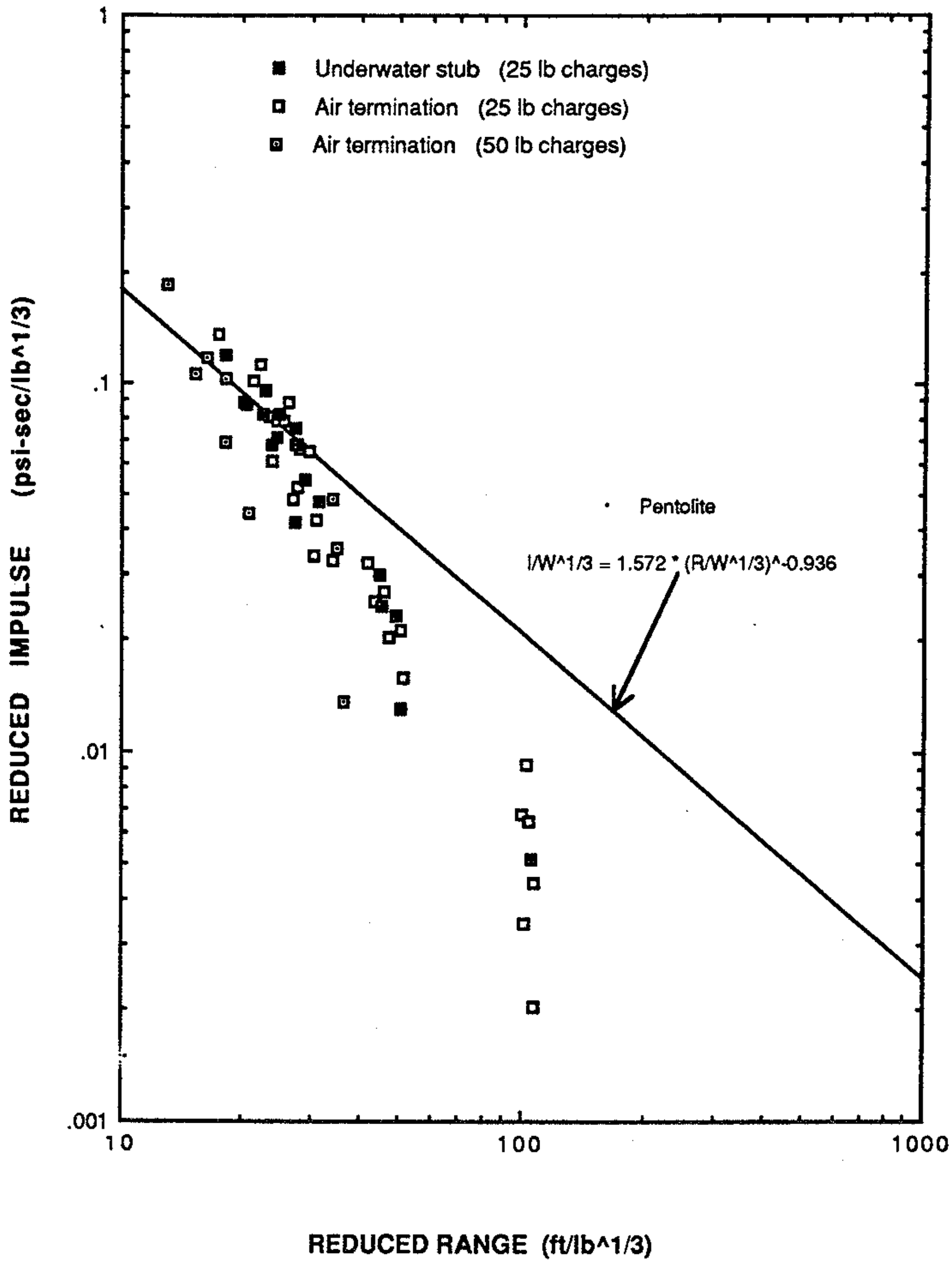


FIGURE 6-5. BUBBLE SHOCK IMPULSE FROM WELL CONDUCTORS

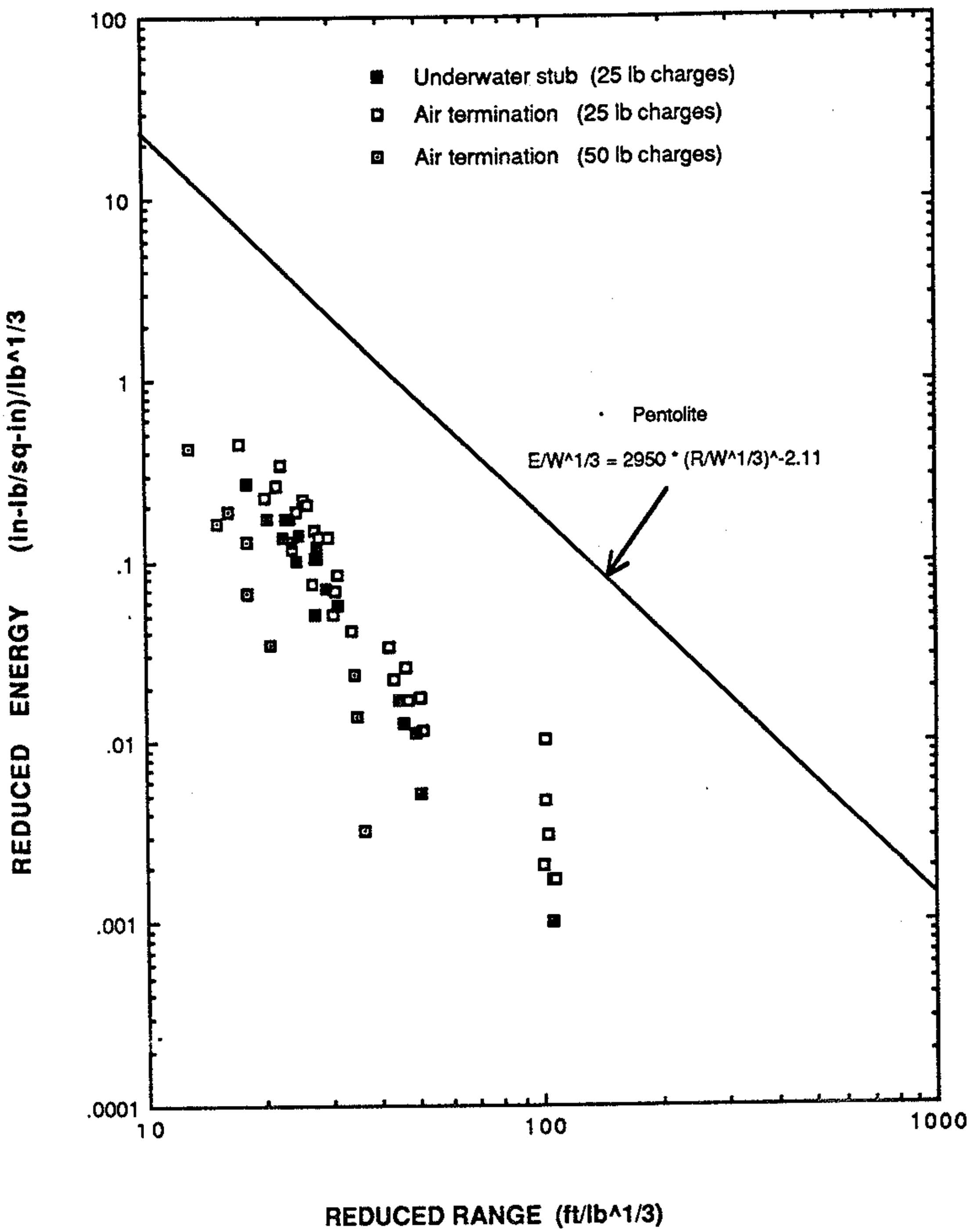


FIGURE 6-6. BUBBLE SHOCK ENERGY FROM WELL CONDUCTORS

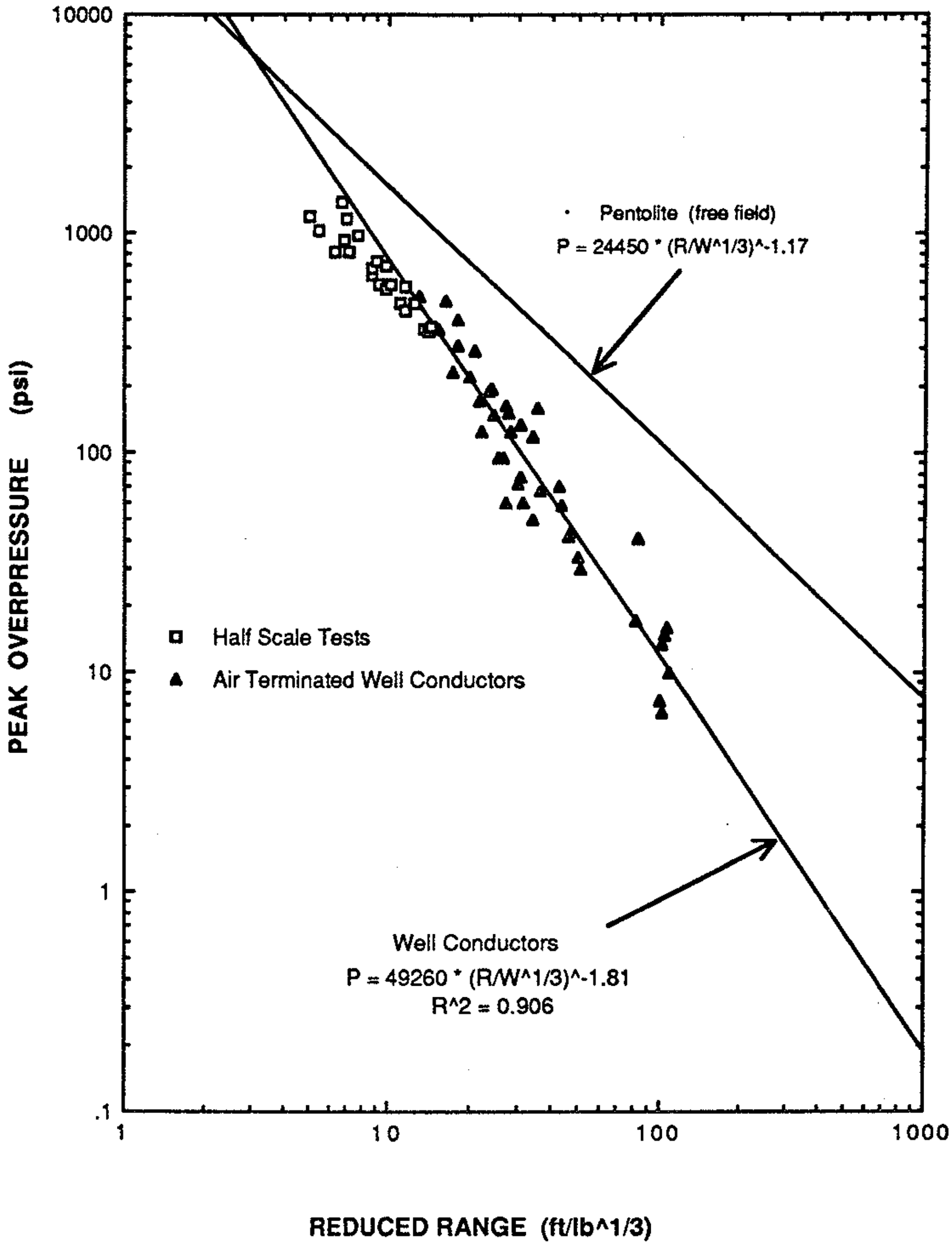


FIGURE 6-7. DIRECT SHOCK OVERPRESSURE (WELL CONDUCTORS VERSUS HALF-SCALE TESTS)

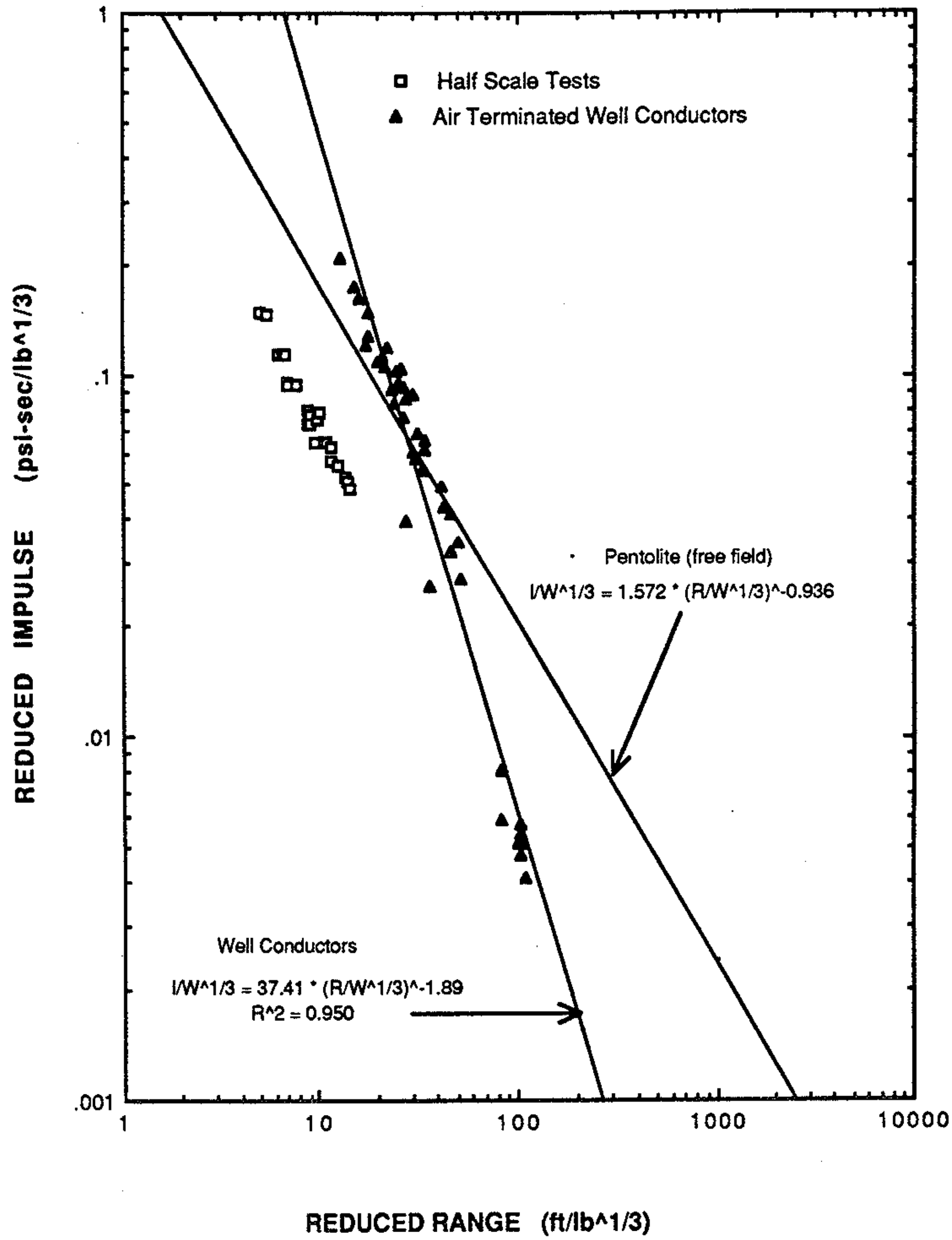


FIGURE 6-8. DIRECT SHOCK IMPULSE (WELL CONDUCTORS VERSUS HALF-SCALE TESTS)

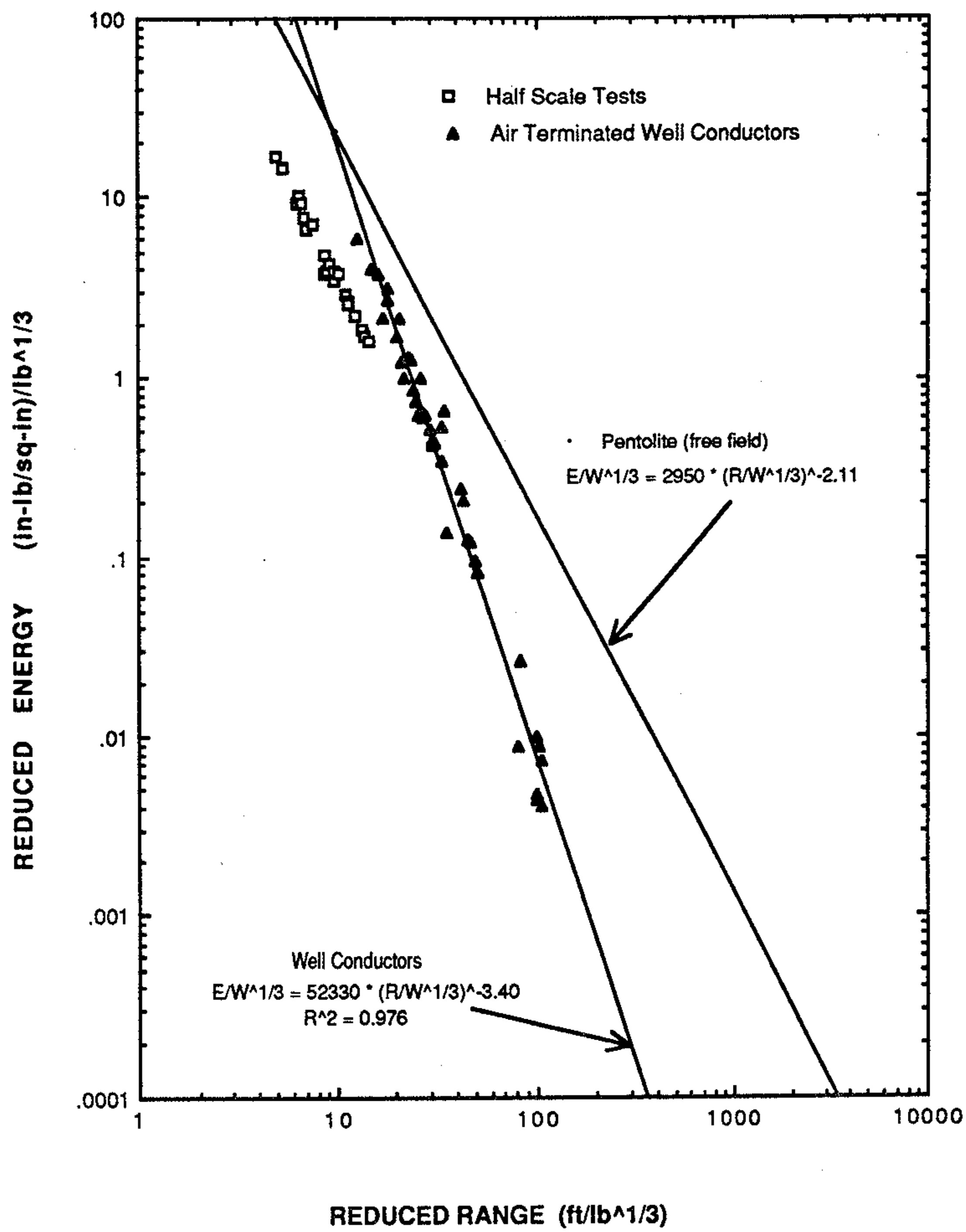


FIGURE 6-9. DIRECT SHOCK ENERGY (WELL CONDUCTORS VERSUS HALF-SCALE TESTS)

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Underwater shock waves generated by explosive removal of a hydrocarbon production platform from the Gulf of Mexico were monitored. Twenty-six Composition B charges were detonated inside bottom penetrating support members at depths beneath the sea bottom ranging from 8 to 26 feet. Charge weights ranged from 25 to 50 pounds. Twelve tourmaline gauges were placed at three water depths at each of four ranges from each detonation. This data report summarizes the observed characteristics of the underwater shock waves transmitted into the surrounding water. Similitude equations are developed from which tentative predictions may be made for similar explosive removal operations under other conditions. No conclusions are drawn about the effects of shock waves on marine life forms that may be in the neighborhood of such explosions.

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